OPTIMAL TEMPORAL ALLOCATION OF THE MULTI-AQUIFER SYSTEM IN AL-HASSA OASIS, EASTERN SAUDI ARABIA

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الى من أضاؤا لي شموع الأمل لينيروا لي الطريق نحو غد مشرق

الى من ضحوا بكل غال و نفيس ليرسموا الابتسامة على محياي

الى أمي الغالية أم عبدالرحمن العبدالقادر

الى زوجتي الفاضلة أم مالك الملحم

الى أبنائي الأعزاء مالك و ناصر

In the Name of Allah, the Most Beneficial, the Most Merciful

DEDICATION TO

Whoever ignited candles of hope to lighten my way toward a brilliant future, and whoever sacrificed to draw a smile on my face

To my precious mother , Umm Abdulrahaman
To my great wife, Umm Malek
To my dear kids, Malek and Nasser

CHAPTER I

INTRODUCTION

The national development planning processes have clearly recognized that water is the most fundamental natural resource in Saudi Arabia. Availability of water is a limiting key factor in the long-term development. The challenge is to meet the water needs of the various national sectors through efficient exploitation of the available water resources at least cost and without unnecessary exhaustion of the non-renewable water reserves (Fifth Development Plan, 1990).

A considerable increase in the national water supply was achieved during the preceding development plans to meet the needs for the various national sectors. By the end of 1993, 27 desalination plants were in use with a daily total production of 2.1 million cubic meters (MCM) of the desalinated water. The utilization of the renewable water resources such as surface water and shallow aquifers has almost doubled since 1980 through an increase in the number of operating dams. The total number of the operating dams increased from 161 in 1985 with a combined capacity of 386 MCM to 184 in 1993 with a total capacity of 482 MCM (Agricultural Statistical Year Book, 1993-1994).

Further development of surface water along with an expansion of the desalinated seawater will remain key elements in future development plans. Yet, neither source of water can be considered reliable because of the natural limitations of the surface water and the high cost associated with the desalination water.

Table I illustrates the development of the national water resources between 1980-1990. Dependence on non-renewable water sources to meet the national water needs increased from 50 percent in 1980 to about 83 percent in year 1990. Irrigated agriculture consumed about 90 percent of the total water supply in year 1990.

The Ministry of Agriculture and Water (MOAW) has completed estimates of proven reserves in the principal and secondary water-bearing formations. These estimates are of high quality in comparison to the similar estimates of the other developing countries. Yet, even more precise information about potential groundwater reserves will be required for future planning. Based on the preliminary estimates, future water use will reach a critical level at which water consumption will far exceed the sustainable water supply. The further development and use of water resources at the local, regional, and national levels should be carefully planned to minimize future water emergencies. However, the national water

TABLE I

ANNUAL NATIONAL WATER BALANCE
IN SAUDI ARABIA, 1980-1990.

(MILLION CUBIC METERS)

	1980	1985	1990
Water Demand			
Municipal & Industrial	510	1200	1650
irrigated Agriculture	1850	7400	14580
Total Water Demand	2360	8600	16230
Water Supply			
Renewable water	1140	1850	2100
Desalinated Water	50	330	540
reclaimed Waste Water	--	100	110
Non-renewable Water	1170	6320	13480
Total Water Supply	2360	8600	16230

Source: MOFANE, Fifth Development Plan. Saudi Arabia, 1990.

Plan has not been finalized because of the lack of data.

The availability of water will limit many aspects of economic and social development. The lack of accurate information has become a substantial barrier to effective national planning because Saudi Arabia relies essentially on non-renewable groundwater reserves as a main water source.

Limited field investigation has been pursued during the last decade to develop estimates of proven reserves in the principal and secondary formations. Simultaneously, the annual extraction from these non-renewable groundwater reserves has increased by more than ten fold. That was due to the rapid expansion in the agricultural sector in general and in particular because of the increase in wheat production.

During the fifth development plan (1990-1995), attempts were made to reduce water consumption in Saudi Arabia through: i)moving agricultural production away from highly water intensive crops; ii) applying conservation measures; and iii)increasing water use efficiency. Accordingly, total water consumption was expected to decline by 8 percent, from 16230 MCM in 1990 to 14875 MCM in 1995. The resulting decline in the national water consumption is attributed to the anticipated reduction in water consumption in agriculture by 13 percent, from 14580 MCM in 1990 to 12675 MCM in 1995.

The reduction in water consumption by agriculture is achieved through: i)changing the crop mix; and ii)adopting more efficient irrigation techniques. Table II presents the anticipated change in the national water use resulting from the conservation measures. The targeted change in water use places more emphasis on increasing the share of the other national water sources and lowering the dependency on non-renewable water resources (Fifth Development Plan, 1990).

Problem Statement

Throughout the last decade, agricultural output grew at a rate unprecedented in the contemporary history of developing countries. Value added by agriculture increased by 13.8 percent per year between 1985-1990, compared to 8.7 percent between 1980-1985. The value added increased by 97 percent, from 11.6 billion Riyals in 1985 to 22.8 billion Riyals in 1990. Consequently, the share of agriculture in the gross domestic product (GDP) increased from 3.4 percent in 1985 to 8 percent in 1990.

This accelerated growth rate was the result of strategic government support of agriculture to meet long-term goals. These goals include: i)achievement of national food security through diversified crop and animal production consistent with available resources and optimal long-term use of water; and ii)achievement of a satisfactory growth rate in production of essential farm products at minimum costs and with efficient use of water.

TABLE II

IMPACT OF WATER CONSERVATION
ON THE ANNUAL NATIONAL
WATER BALANCE.

(MILLION CUBIC METERS)

	1990	1995
Water Demand		
Municipal & Industrial	1650	2200
irrigated Agriculture	14580	12675
Total Water Demand	16230	14875
Water Supply		
Renewable water	2100	2200
Desalinated Water	540	840
reclaimed Waste Water	110	290
Non-renewable Water	13480	11545
Total Water Supply	16230	14875

Source: MOFANE, Fifth Development Plan. Saudi Arabia, 1990.

Agriculture has played and will continue to play a vital role in the national development process through its contributions to: i)the diversification of the national economy; ii)the interaction with the related sectors of the economy; and through iii)the enhancement of the income and welfare of rural residents.

However, the remarkable achievements of the national agricultural sector have been linked to a rapid increase in water consumption which resulted from the spatial expansion in irrigated agriculture and the consequent increase of water use for irrigation. A total of 3.1 million hectares of agricultural land was distributed by the end of 1988, of which one third was devoted to crop farming.

With the rapid expansion in agriculture, large scale projects have relied substantially upon the non-renewable groundwater sources. Around 80 percent of the water for irrigation was drawn from non-renewable groundwater sources. Total water consumption in agriculture increased from 7400 MCM in 1985 to 14580 MCM in 1990, which accounted for 90 percent of the national water consumption. The agriculture sector has become the leading user of the national water resources. This rate of water consumption far exceeds the sustainable water supply. This raises questions about the long-term role of the agricultural sector (Fifth Development Plan, 1990).

Al-Kunait (1995) concluded from estimates of the MOAW that 233,000 MCM of the non-renewable water had been consumed by the agricultural sector in Saudi Arabia within the last 15 years. This was equivalent to about 69 percent of the proven reserves of the principal aquifers. Figure I presents the diminishing path of the Saudi Arabian water reserves. Water reserves declined by about 43 percent from 1980 to 1994, from 491,00 billion cubic meters to 279,00 billion cubic meters over the same period of time.

Table III presents the distribution of water resources among the various sectors in Saudi Arabia. In 1990, 83 percent of the total water consumed came from non-renewable water resources in Saudi Arabia, while only 13 percent came from renewable sources. Desalination provided 3.3 percent, and reclaimed water provided 0.70 percent. Irrigated agriculture consumed about 89.83 percent of the water supply, household consumed 7.64 percent, public services consumed 2.07 percent, and finally industry consumed only 0.46 percent.

The agricultural sector is not only the leading user of the national water resources but also it is the most wasteful and inefficient user of water. Al-Ibrahim (1990) attributed the wasteful and inefficient use of water in agriculture to: i)use of traditional surface irrigation systems with low irrigation efficiency; ii)over-irrigation; and iii)absence of economic incentives and water laws to encourage conservation. Water is given either free of charge or comes from private

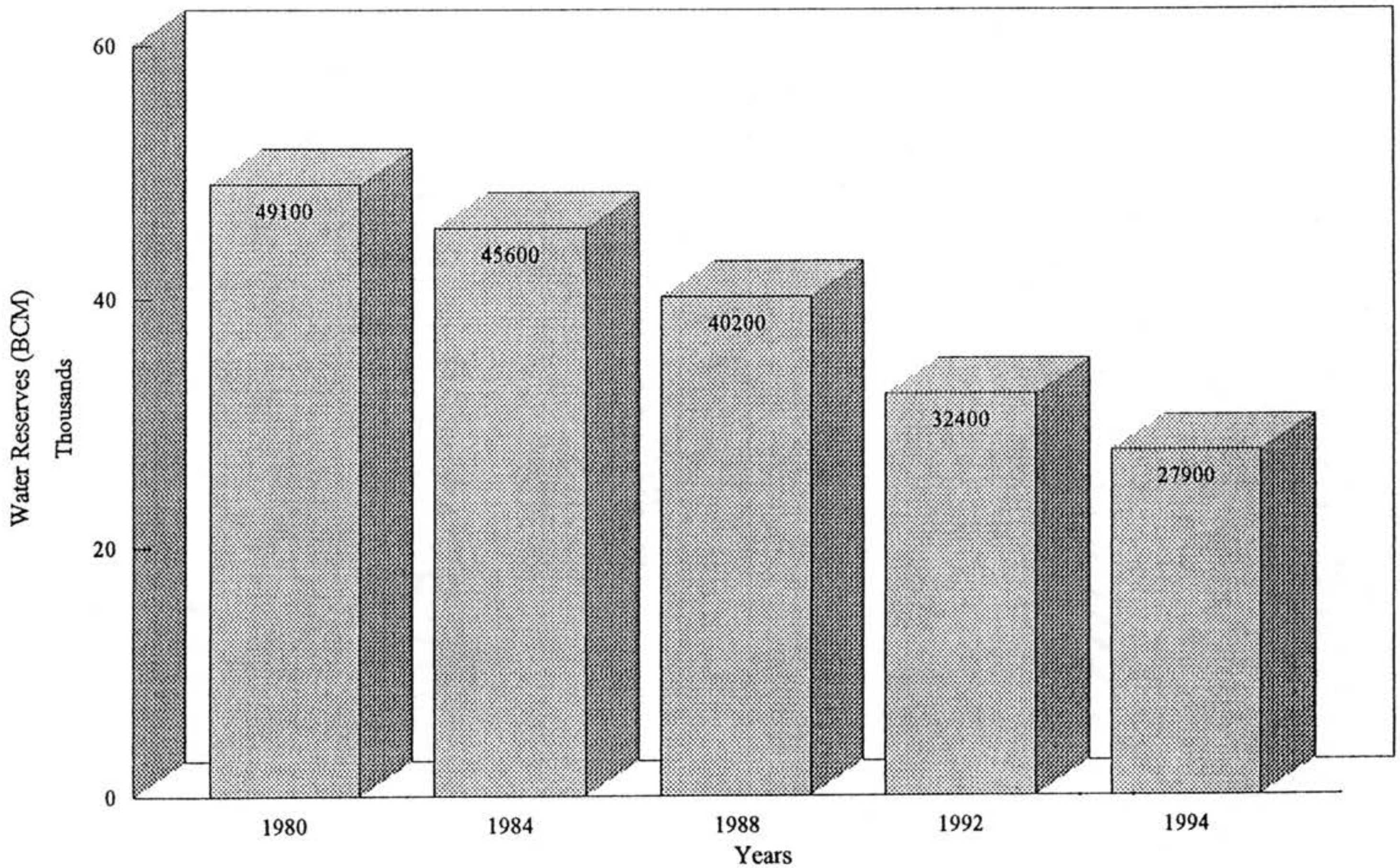


FIGURE I. NON-RENEWABLE WATER RESERVES
IN SAUDI ARABIA, 1980-1994

TABLE III

SOURCE AND UTILIZATION OF WATER BY SECTOR
IN SAUDI ARABIAN, 1990.

Water Source (Supply)	Share Value Percent	Share Value MCM	Consuming Sector	Water Use Percent	Water Use MCM
non-renewable	83.00%	13480	agriculture	89.83%	14580
renewable & surface water	13.00%	2100	household	7.64%	1340
desalinating	3 30%	540	public service	2.07%	336
reclaimed	0.70%	110	industry	0.46%	74
Total	100.00%	16230		100.00%	16230

Source: Al-Zahrani and Mansour. "Possibilities of Water Conservation and Its Priorities Through a National Extension Plan in the Kingdom of Saudi Arabia", 1992.

Share value = the percentage share of a given water resource from the total national water supply.
Water use = the percentage use of water in a given sector from the total national water supply.

Wells.

The issue of water use in Al-Hassa area is the major concern of this research project. Al-Hassa area is one of the largest irrigated areas in Saudi Arabia. The area is located in an arid zone where it is surrounded by desert: the Dhana in the west, sand dunes in the north, Sabkhas in the south and east stretching to the Arabian Gulf (El Khatib, 1980). The oasis extends approximately from 25° 30′ latitude north and 49° 34′ longitude east (MOAW, 1994). Figure II shows the location of Al-Hassa area.

The arable land of Al-Hassa area has been cultivated by traditional methods and used to produce mainly dates, rice, alfalfa, and vegetables. The productivity of most land is poor because irrigation water is reused from field to field through open canals. As a result, the reused irrigation water becomes saline. The productivity of the agricultural land is also reduced by waterlogging.

Irrigation methods are mainly traditional and influenced by the social status of the landlords. Consequently, it is difficult to introduce new methods of irrigation. The water from free-flowing springs is jointly owned by a group of farmers through ancient rights. The landowners who had the largest water share under these rights received the lion's share in both quantity and quality of water. Downstream landowners suffered diminishing benefits because of reduced

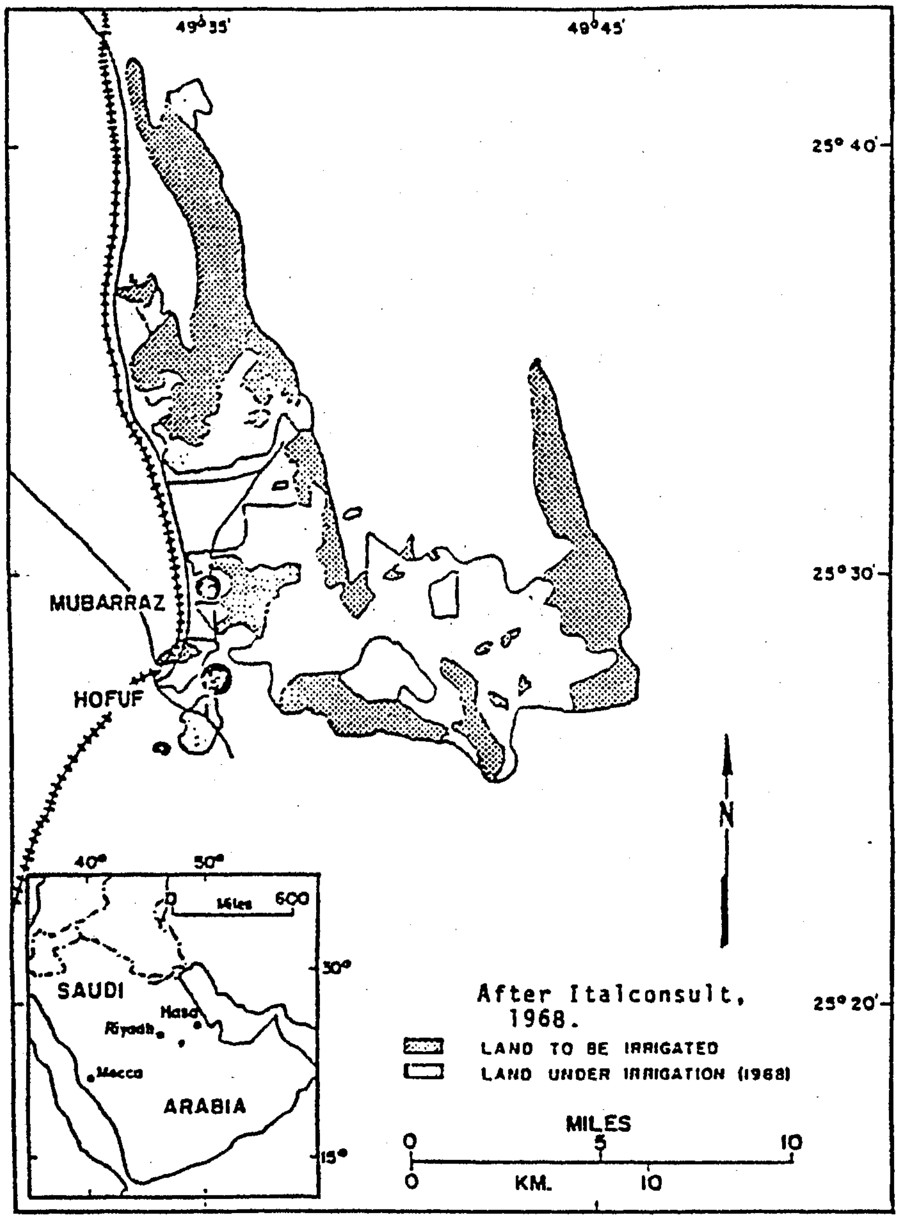


FIGURE II. MAP SHOWING THE LOCATION
OF AL-HASSA AREA

quality and quantity of water. Therefore, many landowners dug their own wells to obtain better quality of water to irrigate their lands.

Irrigation in Al-Hassa area was governed by the natural flow of water from springs. A great amount of the natural flowing water was wasted in winter because few crops were grown. However, the water supply in the summer limits the cultivated area. This natural flow of water originated mainly from three principal aquifers: the Neogene, the Dammam, and the Umm-Er-Radhuma. Even though more than 75 percent of the natural water flow comes directly from the Neogene aquifer (El Khatib, 1980), it is likely that most of water flow in Neogene originally comes from the underlying Umm-Er-Radhuma aquifer (Othman, 1983; WAOSA, 1984).

Around 93 percent of the total natural water flow in the area is consumed by agriculture (Othman, 1983). Like the other parts of Saudi Arabia, water from the area has been used inefficiently by agriculture in general and crop farming in particular. Surface runoff, deep percolation on farm fields, administrative waste, seepage from canals, laterals, and farm ditches as well as evaporation are among other causes that contribute to inefficient and wasteful use of water in agriculture (Humaidan, 1980).

Improving the national benefits from agricultural water use in Al-Hassa area requires a thorough analysis that ensures that groundwater is allocated optimally among the most potential uses both now and in the future. It is necessary to study the complete regional groundwater system in order to understand the groundwater hydrology in Al-Hassa area. Unless efficient methods of water management are adopted and implemented in the area's crop farming sector, the water issue will become more complicated in the near future.

The Overall Objective

The overall objective is to develop and test a preliminary model that can be used to determine the optimal temporal allocation of water from the multi-aquifer system in Al-Hassa area which maximizes discounted net social benefits.

The specific Objectives

1)Determine the optimal one-year investment and resource utilization that maximizes consumer and producer surplus in Al-Hassa area using surface, sprinkler, and trickle irrigation systems.

2)Determine the consequences of future development on the reserves of the multi-aquifer system in Al-Hassa area.

3)Determine the optimal temporal investment in irrigation wells, irrigated lands, annual water use, and distribution systems that yields the greatest discounted net social benefits (NSB).

Research Project Organization

The remainder of this study is subdivided into four chapters. Chapter II is a review of literature that includes historical background information about the study area and related studies pertaining to this research project. The methods and procedures used in the study are presented in Chapter III. Chapter IV discusses the data, analysis, and findings of the study. Finally, the summary and conclusions are presented in the last chapter of the study.

CHAPTER II

BACKGROUND AND REVIEW OF LITERATURE

This chapter is divided into two parts: historical background information and a review of literature relevant to the study. The historical background includes a discussion about: i)the Kingdom of Saudi Arabia with emphasis on the Eastern Province; ii)the national water resources with emphasis on the Umm-Er-Radhuma aquifer; and iii)Al-Hassa area. The second part of the chapter focuses on: i)the review of literature; and ii)the potential contribution of this study.

HISTORICAL BACKGROUND

I. THE KINGDOM OF SAUDI ARABIA

Introduction

Saudi Arabia extends over an area of about 2.25 million square kilometers which is equivalent to about four-fifths of the Arabian Peninsula (El Khatib, 1980). The Arabian Peninsula extends between latitude North 12° and North 38°. The Peninsula is only 12° above the equator. This location makes the Peninsula a hot desert zone (Al-Ibrahim, 1990). It is difficult to acquire dependable statistics about population in

Saudi Arabia. That is because of the continuous movement of the nomadic Bedouins to wherever they find grazing and water (El Khatib, 1980). However, the total national population was estimated to be 16.2 million in 1990 (Urban and Nightingale, 1990).

Meteorology

The Arabian Peninsula is characterized by a hot climate which is subjected for most of the year to northerly winds moving from the eastern Mediterranean toward the Arabian Gulf. Average annual air temperature is 33.4 C° in summer and 14 C° in winter (El Khatib, 1980). Average daily temperature during the summer months exceeds 38 C° and sometimes reaches 49 C° in the eastern, central, and western parts of the nation (Al-Ibrahim, 1990). Relative humidity is low except along or near the coastal zone where it exceeds 90 percent.

Precipitation in the upper two-thirds of the nation is extremely low, unpredictable, and erratic. There is high variation from one year to another and long periods without rain. Rainfall is very local when it occurs and often takes the form of violent storms of short duration. The intensity of the rainfall during such storms is far in excess of the capacity of the land to absorb it. Thus, the high rate of runoff leads to a rapid filling of wadi beds and sometimes severe erosion and destruction. The average annual rainfall is less than 100 millimeters. Most of it falls between December and March and serves mainly for the development of range vegetation (El Khatib, 1980). The average annual rainfall varies from 20 millimeters in the northern part of the nation to 500 millimeters in the southern part of the nation (Al-Ibrahim, 1990).

Soils

Saudi Arabia contains three main geologic regions: the Coastal Plains, the Arabian Shield, and the Sedimentary Basin. The soils in these geologic regions, except for wadis and oases, are generally coarse textured and shallow overlying lithic or paralithic contact. The subsoil often contains gypsic and/or clacic horizons. The common soils in those zones are members of the great soil groups: i)Torripsamments; ii)Calciorthids; and iii)Gypsiorthids.

About 40 percent of the Arabian Peninsula as well as Saudi Arabia are overlain by three vast areas of sand and dunes: i)the great Nefud that covers some 375000 km^2; ii)the Rub Al-Khali desert which extends for about 1200-1500 km North-East to the Arabian Gulf, and iii)the Dhana Desert that connects the great Nefud with the Rub Al-Khali. Because of the arid climate and physiographic features of Saudi Arabia, the desert soils which cover the greater parts of the nation are mostly saline and alkaline.

Agricultural Lands

Agriculture in Saudi Arabia has traditionally centered around scattered oases and wadi channels where springs and shallow groundwater are available or where rainfall alone is sufficient for cropping. In the past, Saudi Arabia did not have secondary industries for processing agricultural products. This was because of the harsh climatic conditions and a lack of irrigation water for agriculture. The lack of irrigation water, the absence of adequate storage facilities, and the high cost of transportation restrained efforts to expand national production above the subsistence level (El Khatib, 1980).

Exports of agricultural products have been limited to non-perishable commodities such as wheat, dates, and livestock. Some vegetables such as onions, potatoes, tomatoes, and watermelon are exported to neighboring countries. Between 1987 and 1990, average annual exports of agricultural products were 1.7 million tons, 85 percent of which was wheat. Over the same period, total F.O.B. export values increased from 835 to 1174 million Riyals.

Imports of agricultural products, on the other hand, declined by about 55 percent between 1987 to 1990, from 7904 to 3569 million tons respectively. Consequently, the C.I.F. value of imports fell over the same time period by 12 percent, from 7332 to 6450 million Riyals (Agricultural Production and its Impact on Foreign Trade, 1994).

Land ownership particularly in cultivated regions has relied mainly on memory because there is no central land registry authority through which ownership of land can be established. There are four main categories of land ownership: the dead or waste land, public land, private land, and waqf (private property handed over to religious foundations). The average size of farm holding is estimated at about 2.2 hectares. The irrigation regimes vary from one area to another and there is no apparent principle of organization.

Hydro-Agricultural Surveys (HAS)

In 1964, the Ministry of Agriculture and Water (MOAW) was entrusted with the task of developing national land and water resources to increase agricultural production and improve the living conditions of the rural population and the Bedouins. Saudi Arabia has been divided into eight regions with boundaries based on both hydrological and topographical features. The rational behind such subdivision of the country was to implement national hydro-agricultural surveys (HAS).

An agreement was made in 1964 between MOAW and Food and Agriculture Organization of the United Nations (FAO) for an advisory team to assist in supervising studies which were to be carried out by the selected international consultant firms. Five out of the eight areas had been surveyed by 1970. This covered about 57 percent of the total area of Saudi Arabia. These five areas are: i)the Great Nefud Sedimentary Basin which covers some 375 thousand km^2; ii)South-West Saudi Arabia which covers some 250 thousand km^2 ; iii)Eastern Saudi Arabia which covers 362 thousand km^2; iv)Region of Riyadh which covers about 108 thousand km^2; and v)the Red Sea Coast which covers 190 thousand km^2.

The purpose and scope of HAS were: i)determine the quality, quantity, and location of the national water resources; ii)determine crop land and range potentialities; and iii)suggest means to improve the living conditions of the rural population and the settlement of nomads. The HAS provided the MOAW with an information base for a better national agricultural policy. Some of the results of these surveys are summarized in *Table IV*.

EASTERN SAUDI ARABIA

General Features

Eastern Saudi Arabia (ESA), the fourth hydro-agricultural area of Saudi Arabia, covers about 362 thousand km^2. It comprises the eastern and part of the northern regions of Saudi Arabia. The area includes the coastal belt where three of the great agricultural development projects: Al-Hassa, Qatif, and Faisal Settlement Project at Haradh are located. Also, it includes Wadi Al-Miyah, and Yabrin area. For the study purposes, ESA is divided into four subregions based on the differences in physical features; socio-economic aspects; natural resources; and development possibilities. A map

TABLE IV

NATIONAL WATER AND LAND RESOURCES BASED ON RESULTS OF HYDRO-AGRICULTURAL SURVEYS

Variable	Unit	Total
Area	km^2	1281000
Precipitation:		
Depth	mm	90
Volume	MCM	1200000
surface Runoff	MCM	2400
Infiltration:	MCM	
Present Direct		700
Induceable		Uncertain
Groundwater Storage	MCM	Vast
Groundwater Extraction	MCM	2000
Groundwater Potential:	MCM	
from Recharge		325
from Storage		1700
Surface water Potential	MCM	400
Cultivated Land	ha	363000
Potential Arable Land	ha	4244000
Total	**ha**	**4607000**
Range Land:	ha	
Excellent Range Land		10188437
Good Land		37557168
Fair Land (not denuded)		39251445
Poor Land (completely Destroyed)		33674775
Total	**ha**	**120671825**

Source: El Khatib, Seven Green Spikes. Saudi Arabia, 1980.

showing the four regions of the ESA is presented in *Figure III*.

The first subregion covers 31000 km^2 extending from the northern border of Saudi Arabia with Kuwait to Haradh area in the south. This subregion is the backbone of ESA area, having a vast amount of water resources as well as fertile lands. Most of the Kingdom's irrigated agricultural area is located here. Furthermore, this region has a leading function in the national economy since it contains the largest portion of the nation's oil fields, refineries, and other infrastructure.

The second subregion is mainly desert where it extends from Al-Jafurah east and latitude 25° in the west to the Rub Al-Khali south. It covers about 150,000 km^2 and surrounds the southern part of the first region. In contrast to the first region, the second region lacks water resources and has salinity and drainage problems, thus, no agricultural settlements exist there. However, there are a few fishing centers which reside on the coast as well as Yabrin oasis which is the only large oasis with scattered groups of 50 to 60 thousand date palm trees. Accordingly, the population of this region which is mostly nomadic represents only about 6 to 7 percent of the total population in ESA area.

The third subregion covers about 53000 km^2. It lies between the western border of the first region and the northern border of the second region. Even though no urban

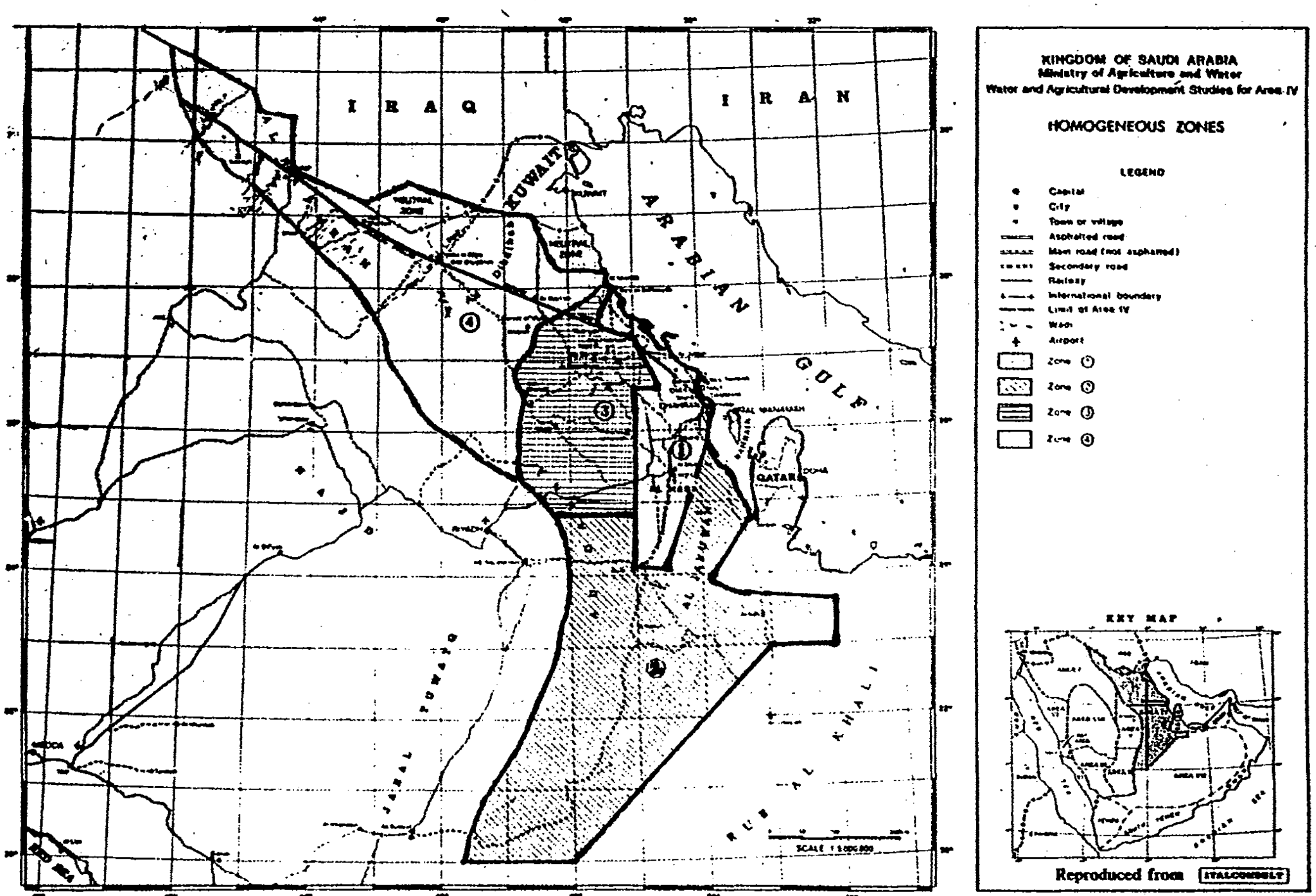


FIGURE III. MAP SHOWING LOCATION OF THE FOUR REGIONS IN EASTERN SAUDI ARABIA settlements exist in this subregion, a few industrial and modern service centers do exist along its borders. Agriculture in this subregion is located mainly in small oases such as Wadi Al-Miyah and Qaryat. Also, there are grazing areas to the north-east and south of the subregion.

The fourth subregion covers about 128 thousand km^2 which covers mainly the north-western portion of ESA area. It contains the second most important grazing lands of all ESA area. About 80 percent of the total regional population, though less than 20 percent of the ESA total population, is nomadic or semi-nomadic. Livestock in this subregion depend on the winter pastures of the Nefud and Dhana and on the summer pastures north of the Dhana where a few hand-dug wells exploit groundwater resources in the area.

General Geological Features and Formations

The ESA area is underlain mainly by marine limestone, sandstones, and shale deposits formed since the Paleozoic era. The western border of ESA area is the outcrop of the boundary between the upper-most Cretaceous (Aruma formation) and the Basal Tertiary (base of Umm-Er-Radhuma formation). The general dip of the strata is interrupted in the eastern part bordering the Arabian Gulf by a series of folds oriented mainly in a north-south direction. A large portion of ESA area is free of sand, though sand dunes are prominent in the regional coastal belt.

Another prominent feature of the ESA area is the Quaternary gravel covering plains like those around Wadi Batin in the north and from Haradh south to the Rub Al-Khali. The gravel are formed mainly of quartz and metamorphic pebbles from the basement, implying the existence of a considerable developed surface hydro-graphical pattern. Such a pattern most probably resulted from a rainy climate in some unspecified period.

The ESA area relies mainly on groundwater resources for its current supplies and future development. Hydro-geological information showed that water of useful quality is obtainable within an economic depth in various parts of the area from the Umm-Er-Radhuma formation and at a greater depth from the Wasia formation. The salinity increases from west to east throughout all water bearing formations in the area.

The ESA area overlies many water-bearing formations which are in ascending order as follows: i)Thamma Group; ii)Wasia formation; iii)Aruma formation; iv)Umm-Er-Radhuma formation; v)Rus formation; vi)Dammam formation; and vii)Neogene formation.

Thamma Group (Lower-Upper Cretaceous Age): The thickness of Thamma group ranges from 107 meters in the north of area IV to 1800 meters in the Rub Al-Khali. Hydrologically, the Biyadh formation is the most important formation in the Thamma group especially along a belt closer to the outcrops where water salinity is low (El Khatib, 1980). The Biyadh formation slopes gently to the southeast, east, and northeast from its outcrop. The thickness of the Biyadh formation is about 425 meters at the outcrop and thins eastward to 100 meters near the Arabian Gulf (WAOSA, 1984).

Wasia Formation (Middle-Upper Cretaceous Age): The Wasia formation may be divided into upper and lower formations along the shore of the Arabian Gulf. The Wasia's upper formation is mainly formed of clay, silt clay, and limestone. Whereas, the Wasia's lower formation is mainly formed of massive sandstone with occasional clay inter-calations. The thickness of Wasia formation varies between 42 meters in the typical series to about 500 meters in the Safaniya zone.

From the hydrogeological standpoint, the Wasia formation is the most important Cretaceous formation. The continental sandstone of the lower member is potentially the most productive part of the Wasia formation. Because of its potential hydrologic property, the Wasia formation is a great source of water especially west and south of the great Ghawer structure (El Khatib, 1980). Nevertheless, it is very costly to develop the Wasia formation in eastern Saudi Arabia because of the great depth to the top of the formation. The Wasia and Biyadh formations are one aquifer system in most of central Saudi Arabia. However, they are separate formations in eastern Saudi Arabia (WAOSA, 1984).

Aruma Formation (Upper Cretaceous Age): The Aruma formation lies unconformably on the Wasia formation. It consists mainly of limestones, grey, tan, buff and sometimes fossiliferous with inter-calations of dolomitic limestone, dolomitic marl, chalky limestone, and subordinate clay (El Khatib, 1980). The thickness of Aruma formation varies from about 35 to 140 meters at central and north-western Saudi Arabia, respectively (Othman, 1983).

Umm-Er-Radhuma Formation (Paleocene Age): The Umm-Er-Radhuma formation is potentially of great importance as a plentiful water source for domestic and agricultural uses. The upper part of the formation is the most productive. It is the most important formation of the Tertiary age. Water salinity ranges normally from less than 1000 to 6000 parts per million (PPM) at the eastern edge (El Khatib, 1980).

Rus Formation (Lower Eocene Age): The Rus formation is of little importance regionally and locally because of its overall poor permeability (El Khatib, 1980). It acts as a confining bed with an average thickness of 55 meters. It is formed mainly from marl, chalky limestone and gypsum (WAOSA, 1984).

Dammam Formation (Middle Eocene Age): The Dammam formation is divided into five members, ascendingly as follows: i)the Midra Shale; ii)the Saila Shale; iii)the Alveoline Shale; iv)the Khubar limestone; and v)the Alat limestone. The Alat and Khubar members are persistent except in the northern-east. The combined thickness of Alat-Khubar members comprises about two-thirds of the Dammam formation, even though the thickness of any of these two members rarely exceeds 25 meters (WAOSA, 1984).

Economically, the Khubar-Alat members are the most exploitable formations in the Dammam formation. Because of its relatively shallow depth, the Khubar member is the most important formation in the ESA. The Alat member is also of a great importance in spite of its variable permeability (El Khatib, 1980).

Neogene Formation (Miocene-Pliocene Age): The name of the Neogene formation is given collectively to an extensive variable series of beds of the Miocene and Pliocene ages. The Neogene formation is subdivided ascendingly into the following members: Hadrukh; Dam; and Hufuf. The average thickness of the individual member ranges from 20 to 120 meters. The Dam member of the Neogene formation is the major formation in Al-Hassa Area. It is a substantial source of water locally in the eastern Saudi Arabia near the Arabian Gulf. The Neogene formation has been heavily developed in areas around the Al-Hassa area and along the eastern edge of the Qatif area (WAOSA, 1984).

Meteorology

With the exception of the Rub Al-Khali basin, Eastern

Saudi Arabia lies within the winter rainfall zone. The climate ranges from arid to desert. Temperature is high in the summer season and rainfall is scarce in greater parts of the area. The mean annual rainfall does not exceed 100 millimeters except along the coastal zone. A very preliminary analysis showed that areas north of Wadi Batin receive low rainfall. Areas south of Wadi Batin have a probability of higher rainfall. The vegetation south of the latitude of Al-Hassa Area indicates that rainfall is more intense with lower seasonal totals. Humid climate is experienced year-round along the coastal belt and for a few kilometers inland which is mainly due to the proximity of the Arabian Gulf. Maximum humidity occurs in the mid-winter and to a lesser extent in the mid-summer seasons.

Water Resources

Hydrogeological investigations in the ESA have concluded that the most important water-bearing sedimentary formations are those extending upward from the Wasia to the Neogene. The Umm-Er-Radhuma formation has the greatest overall potential for development. The Khubar formation has great potential for development in the coastal belt area. The Alat formation has a more moderate potential for development. The Neogene formation has a high potential for development in Al-Hassa area because of its higher transmissivity. However, in all other parts of the ESA, the Neogene formation has rather a low potential for development. All water-bearing formations especially those composed of limestone show great variability in their productive capacity, coefficient of permeability, and total porosity. The quality of groundwater is generally related to groundwater movement. The higher the permeability and flow rate, the better groundwater quality. The formations are separated from one another by impervious layers. Yet, the impervious layers are not always continuous because of fractures or/and formation thinning. Hence, leakage occurs between one aquifer and another in some areas. Generally, the deeper aquifers leak to those lying above. For example at Al-Hassa the Neogene carries water coming from the underlying Umm-Er-Radhuma formation and probably from the Wasia formation (El Khatib, 1980).

Water Extraction

In 1980, it was estimated that 675 million cubic meters (MCM) were extracted annually from the various water-bearing formations lying in the ESA. *Table V* shows the break down of the total annual water extraction from the different formations in the area. Most of the water is tapped from shallower aquifers in the coastal belt and Al-Hassa area. Also, there is a considerable water discharge from the shallower aquifers to the Arabian Gulf through an undetermined number of submarine springs. Furthermore, about 175 MCM annually is tapped from the Alat-Khobar formations on Bahrain.

TABLE V

TOTAL ANNUAL WATER EXTRACTION FROM THE VARIOUS WATER-BEARING FORMATIONS IN EASTERN SAUDI ARABIA

(MILLION CUBIC METERS)

Aquifer	Coastal Belt	Al-Hassa	North Area[1]	South Area[2]	Total
Quaternary &Neogene	0.350	422.6	4.810	0.02	427.780
Alat	32.205	0.045	3.255		36.505
Khobar	22.545	0.445	1.150		24.140
Alat & Khobar	124.240	0.015			124.255
Umm-Er-Radhuma	21.740		4.620	1.57	27.930
Aruma			0.035		0.035
Wasia			0.035		0.350
Others	33.560		0.480	0.54	34.580
Total	234.640	423.105	14.385	2.13	674.260

North area is north of Riyadh-Dharan highway.
South area is south of Riyadh-Dharan highway.
Source: El Khatib, Seven Green Spikes. 1980.

Land Resources

Potentially, about 150 thousand km^2 of the total lands of the ESA are arable and/or grazing lands. However, water availability rather than soil fertility is the limiting resource to the agricultural development in the region. Regional agricultural development in the area relies mainly on groundwater because rainfall is low and surface run-off is negligible. Previously, shallow aquifers as well as natural flowing springs of deep confined aquifers such as that of Al-Hassa area were the main sources of water. However, new groundwater sources have been located which potentially provide agriculture with abundant quantity of water (El Khatib, 1980).

II. WATER RESOURCES IN SAUDI ARABIA

Potential national water resources exist naturally in the form of groundwater and surface water. The sources are not always separated. They are hydrologically connected at some places. Such connection occurs when surface runoff infiltrates into the subsurface to form groundwater. Then, groundwater emerges at different places as natural springs or as base flow in wadis. Next, water in wadis flows to the sea, evaporates to the atmosphere, or infiltrates into the subsurface.

Groundwater is the most essential water source in Saudi Arabia. It accounts for more than 83 percent of the national water resources (Fifth Development Plan, 1990). About two-thirds of Saudi Arabia is underlain by sedimentary formations which consist mostly of sandstone, limestone, shales, marles, and alluvium. Sandstone and limestone formations are the main sources of groundwater. Recent water resource studies have located many water-bearing formations with vast amounts of stored water. However, earlier discoveries of such water-bearing formations led to irrational and hasty drilling and uncontrolled extraction from many wells, with little concern to the water requirements and drainage facilities of the land served (El Khatib, 1980).

Groundwater comes from two types of aquifers: renewable or shallow aquifers and non-renewable or deep aquifers. The estimated annual capacity of renewable groundwater aquifers is about 950 MCM. Whereas, the total non-renewable groundwater is estimated at about 500,000 MCM (Fourth Development Plan, 1985). Around 51 to 67 percent of the proven non-renewable groundwater is stored in seven principal aquifers, while the rest is stored in a series of secondary aquifers (Fourth Development Plan, 1985; Abdulrazzak and Khan, 1990; Al-Ibrahim, 1990). The distinction between principal aquifers and secondary aquifers is based on hydrologic properties and areal extent. The principal aquifers have larger yield and greater permeability than the secondary aquifers (WAOSA, 1984). The seven principal aquifers are: i)Saq, ii)Tabuk, iii) Wajid, iv)Minjur, v)Wasia, vi)Umm-Er-Radhuma, and vii)Dammam (Abdulrazzak and Khan, 1990).

The actual proven reserves of the principal aquifers in Saudi Arabia have not been precisely estimated. *Table VI* presents a summary of the non-renewable reserves in the Saudi Arabian principal aquifers along with their mean annual recharge. The table presents two different estimates of proven reserves, reflecting the uncertainty of groundwater deposits. However, there is consensus between both estimates that Wasia aquifer has the largest proven reserves of all.

Surface water is the second essential water source in Saudi Arabia. The potential annual supply of surface water is estimated at about 900 million cubic meters if the existing dams are used efficiently (Bahanshal, 1989; Al-Ibrahim, 1990).

Surface water occurs as runoff, reservoirs, and lakes. *Runoff* is that part of rainfall which occurs either as: i)surface flow in wadis which infiltrates the alluvial deposits within the wadi where it generates sub-surface flow recharging groundwater; or ii)overland sheet flow, some of which eventually moves toward wadis where it becomes part of the surface flow. Runoff generally is erratic and scarce in Saudi Arabia (WAOSA, 1984). Mean annual surface runoff is estimated at about 2000 MCM, of which 30 percent is diverted for agriculture, 45 percent is infiltrated to recharge groundwater aquifers, and 25 percent is lost to evaporation

TABLE VI

SUMMARY OF GROUNDWATER RESERVES IN THE SAUDI ARABIAN PRINCIPAL AQUIFERS.

(MILLION CUBIC METERS)

Aquifer	Annual[1] Recharge	Water Reserves			
		Proven[1]	Proven[2]	Probable[1]	Possible[1]
Saq	205	65000	49900	100000	20000
Wajid	104	30000	69000	50000	100000
Manjur & Dhruma	80	17500	53400	35000	85000
Wasia	480	120000	89000	180000	290000
Umm-Er-Radhuma	406	16000	65600	40000	75500
Dammam	200	5000	5000	NA	NA
Tabuk	455	560	5600	NA	NA
Total	1930	254060	337500	405000	750500

Sources: 1)Abdulrazzak and Khan, "Domestic Water Conservation Potential in Saudi Arabia." March/April 1990:167-178.
2)MOFANE, The Fourth Development Plan. Saudi Arabia, 1985.

(Abu Rizaiza and Allam, 1989).

Reservoirs are created through the construction of dams. The topography of Saudi Arabia is such that the volume of each reservoir is generally small. Reservoirs of many of the dams in the mountainous area are more than half full most of the year. Most of the constructed dams have been used to control floodwater. This floodwater is released gradually to recharge groundwater which is then used for agriculture and domestic purposes.

Lakes occur infrequently. The Layla Lakes are the largest natural lakes in Saudi Arabia. The lake group is located 17 km south of Layla area. The lakes group was formed by a hydrogeo-chemical solution processes in which some parts of the sedimentary layers under the Layla area were dissolved leaving a series of subsidences. The common gypsiferous deposits around the lakes group implies that a single large lake once covered an area of 175 square kilometers. Then, the area of this lake diminished because of the climatic changes which prevailed in the Arabian Peninsula during the late Quaternary era. Finally, this large lake became 17 small lakes covering an area of about 385200 square meters.

The Saudi government allocated a substantial amount of public investment to develop new water sources including seawater desalination plants and wastewater treatment plants.

The first large-scale desalination plant began operation in Saudi Arabia in 1969. By 1983, Saudi Arabia had become the world's leading user of the desalinated seawater. The utilization of this water source facilitated the national development without affecting groundwater reserves (WAOSA, 1984). During the fifth development plan, 1990-1995, the Saudi government allocated 22,193 million Riyals to develop the national water sector. Three fourths of this amount was used to build new desalination plants and to operate and maintain the existing ones (Fifth Development Plan, 1990). Desalinated seawater accounts for about 3.3 percent of the current national water resources. However, because of the high costs associated with producing and transporting desalinated water to inland cities, seawater desalination cannot be a reliable long-run substitute for groundwater resources (Fourth Development Plan, 1985). The estimated cost of producing and transporting 1 cubic meter of desalinated water to inland cities varies between 20 to 30 Saudi Riyals (Al-Ibrahim, 1990).

Treated wastewater accounts for about 0.7 percent of the current national water supply (Al-Zahrani and Mansour, 1992). Based on studies made in the early 1980's, about 60 percent of the total water consumed in the Saudi Arabian cities at that time flowed into sewage systems as effluent. This wasted water has been recognized as a recoverable water source that could be used to enhance the national water supply in the future.

The treated wastewater could be used in irrigated agriculture as a substitute for the fresh water. Accordingly, the reuse of the treated wastewater has become a prominent source of water in Saudi Arabia (WAOSA,1984).

Approximately 110 million cubic meters of the treated wastewater were recovered in 1990 and used mainly for irrigation and industrial purposes (Fourth Development Plan, 1985; Fifth Development Plan, 1990). This quantity is expected to more than double by the end of 1995 (Fifth Development Plan, 1990) and to increase by tenfold by year 2010 (Al-Ibrahim, 1990).

Umm-Er-Radhuma Formation

The Umm-Er-Radhuma (UER) formation was named for the Umm-Er-Radhuma wells that tap the upper part of the formation. The age of the fauna in the UER is classified into two main geological eras. The upper part is from the early Eocene era and the lower part is from the Paleocene era (WAOSA, 1984). The Umm-Er-Radhuma formation covers around 350000 km^2 in Eastern Saudi Arabia (El Khatib, 1980).

The outcrop of Umm-Er-Radhuma formation extends 1200 km from the northern border of Saudi Arabia with Iraq and Jordan to the south of Wadi Dawasir in a broad band of some 50 to 100 km wide (Othman, 1983;WAOSA, 1984). The formation rocks extend widely south and east underneath the central part of the Rub

Al-Khali desert and crop out again along the southern margins of the same desert. In some regions, however, it is difficult to recognize the formation rocks due to the outcropping of the overlying Neogene deposits and sand of the Great Dahna desert. The formation rocks comprise mainly of a series of light-colored and dense limestones, dolomitic limestones, and dolomites. Marls and shales are found in central and southern areas of the upper part of UER. Significant layers of anhydrite and some chert are found at the northern area of the upper part of the formation. As result of weathering out of a lattice of poorly-cemented dolomite crystals as well as the general enlargement of joint surfaces into fissures, the porosity of the formation upper part is greater than that of the lower part.

The thickness of UER varies from one area to another. It is about 240 meters at the type section in the Wadi Batin and increases east and south to about 435 meters in the Rub Al-Khali basin reaching its maximum north and east of Hufuf where it is about 500 meters and 700 meters, respectively. Then, the formation rocks thin to about 300 meters over the Ghawar anticline. The Umm-Er-Radhuma formation overlies thoroughly the Aruma formation with apparent conformity. However, the relationship becomes more complicated with the overlying formations.

The Umm-Er-Radhuma formation is a single thick hydraulic unit that possesses excellent hydrologic properties and dependability. It is water-bearing throughout greater areas of Eastern Saudi Arabia and the Rub Al-Khali desert as well. The recharge to the UER is minimal. The UER is recharged by the direct infiltration of seasonal rainfall over the outcrop, and runoff from wadis. It was estimated in 1979 that about 7-14 percent of the annual average rainfall that falls on the outcrop in the eastern province infiltrates into the aquifer. Al-Hassa springs receive a substantial water flow of the UER (WAOSA, 1984). Water discharge of the UER varies from one area to another depending on the formation properties in the respective area (Othman, 1983). *Table VII* illustrates some properties of wells penetrating UER aquifer in different areas of the ESA.

Transmissivity of UER is high in areas where karst weathering has occurred in the upper parts of the formation. Whereas, it is low in areas where there is an increased amount of marl (WAOSA, 1984). The average storage coefficient of the UER varies between 5×10^{-5} to 5×10^{-3} m^2/second. The average transmissivity ranges between 4×10^{-5} to 1.1×10^{-2} m^2/second (Othman, 1983; and WAOSA, 1984). The highest value of transmissivity was found to be 6×10^{-1} m^2/second(Othman, 1983).

TABLE VII

SELECTED PROPERTIES OF WELLS PENETRATING THE UMM-ER-RADHUMA FORMATION.

Area Name	Total Depth (meter)	Well Yield (GPM)	Static Water Table (meter)	Dynamic Water Table (meter)	Water Quality (PPM)	Pumping Screen Depth (meter)
Hafr Batin	150-250	85	80	125	2976	100
Umm-Er-Radhuma	200	25	120	150	1165	60
Yabrin	300	1500	+2	5	883	200
AL-Hassa	300-350	1200	40	45	896	250
Haradh	350	1200	60	65	1024	300
Jodah	400	600	20	60	1363	220
Hunayy	450	1000	180	185	1408	300
Eastern Co.	450	1000	70	75	1600	350
Nuiriah	450	380	+35	GS	3584	350
Sarrar	500	120	+10	GS	1696	400
Garyah Al Ulya	550	150	45	140	2304	450
Humatyat	800	80	75	145	5951	700

Source: MOAW, Department of Water Resources Development, 1994.
Total depth = distance from ground surface to bottom of well screening, Screen depth = the distance from aquifer top to well screening bottom, + = above ground surface, GS = ground surface.

III. AL-HASSA STUDY AREA

General Features

Al-Hassa area is located in the Eastern Province of Saudi Arabia, about 70 km from the Arabian Gulf, 150 km south of Dammam, and 320 km northeast of Riyadh (Al-Taher, 1987). It is roughly an L-shaped area and consists of two major parts: the eastern area and the northern area. The eastern area extends from the main town of Al-Hufuf on its western side to 16 km along to the east with an average width of 9 km, totaling about 144 km. The northern area extends from Al-Mubarraz at about 3 km to the north of Al-Hufuf with a total length of 17 km and an average 7 km width.

Meteorology

The climate of the area is subtropical. It is hot and dry in the summer season, mildly cool in the winter season, and pleasantly warm in the fall and spring seasons (Humaidan, 1980). *Table VIII* represents a summary of the average climatological data for Al-Hassa area for the period between 1985-1993. The table shows the predominant meteorological features of the area: high average air temperatures of 33.51 C°, moderate to high air humidity of 40.86 percent, long sunshine hours which average 9 hours per day, strong winds which average 112.17 km/day, and scarce precipitation which averages only 72.32 millimeters per year (millimeter = 0.03937 inch).

TABLE VIII

SUMMARY OF AVERAGE MONTHLY CLIMATOLOGICAL DATA IN AL-HASSA STUDY AREA, 1985-1993.

Month	MaxTemp. (C°)	MinTemp. (C°)	Humidity (%)	Wind (km/day)	Sunshine (hrs)	Rainfall (mm/mon)
JAN.	19.8	7.1	55	102	7.5	8.2
FEB.	22.5	9.2	51	133	7.5	12.8
MAR.	27.5	13.2	43	135	7.2	17.2
APR.	32.9	17.3	41	119	8.1	13.1
MAY.	40.1	22.6	34	137	9.6	1.2
JUN.	42.3	24.6	27	144	9.1	0.0
JUL.	44.2	26.2	28	124	9.3	0.0
AUG.	43.4	25.2	29	108	10.1	0.0
SEP.	41.0	22.5	37	91	9.8	0.0
OCT.	36.9	18.3	43	77	9.6	0.0
NOV.	28.7	13.6	48	80	8.8	0.2
DEC.	22.9	10.1	55	97	7.6	19.6
AVG.	**33.5**	**17.5**	**41**	**112**	**8.7**	**6.0**

Sources:1)MOAW, Department Of the Water Resources Development, Saudi Arabia 1994.
2)Smith, CROPWAT, 1992.

The average monthly maximum and minimum air temperatures are 33.5 C° and 17.5 C°, respectively. Temperatures reach a minimum of 19.8 C° in January and a maximum of 44.2 C° in July. The average monthly air humidity is about 41 percent with a maximum of 55 percent in January and December and a minimum of 27 percent in June. Precipitation is scarce and irregular in the area with a monthly average of 6 millimeters, reaching a maximum of 19.6 millimeters (mm) in December. Therefore, precipitation is not a reliable source for the irrigated agriculture in the Area.

Groundwater Resources

The hydrogeologic studies made by an international consulting firm BRGM concluded that the principal water formations feeding the area are the following: Neogene Complex, Dammam, and Umm-Er-Radhuma. *Figure IV* shows a cross section for the principal water formations in the study area.

The Neogene Complex

Outcropping of the Neogene formation occurs widely throughout the area. The lower and the middle formations of the complex are good reservoirs. The Neogene formation acts as a large intake zone with annual recharge occurring either through direct infiltration of runoff water or through delayed infiltration in the spreading zones located in the numerous depressions west of the Ghawar structure. South of the Ghawar structure, the Neogene formation rests on the Umm-Er-Radhuma

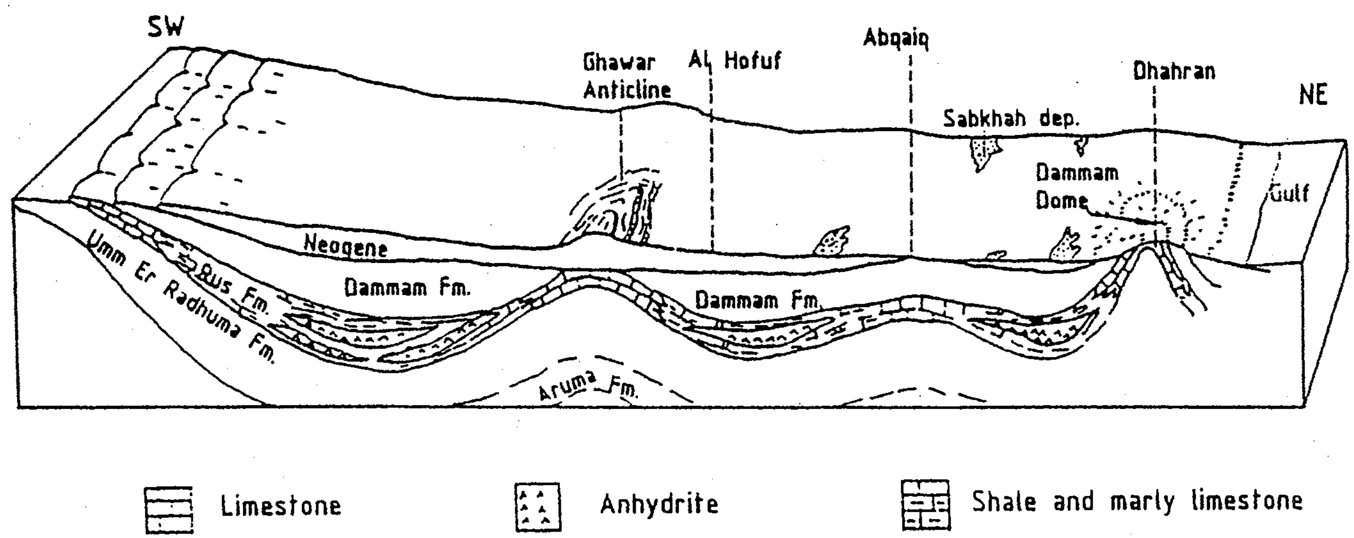


FIGURE IV. A CROSS SECTION SHOWING THE PRINCIPAL WATER FORMATIONS IN AL-HASSA STUDY AREA (Al-Layla et al., 1992) formation.

Because of the connections between the Neogene formation and the underlying formations in the truncating area on the top of the Ghawar structure, the water which flows through the Neogene formation and out as springs is a result of complex mixing. About 75-80 percent of the water originates from the Neogene aquifer, about 10-15 percent is estimated to come from Umm-Er-Radhuma through the Neogene formation, and 5-10 percent comes from annual recharge (El Khatib, 1980). Water in the Neogene formation is likely derived from the upward leakage from the Umm-Er-Radhuma formation especially in Al-Hassa area (WAOSA, 1984).

The mean annual recharge value of the Neogene aquifer is estimated at 10 m^3/second which is roughly equivalent to the water withdrawal of Al-Hassa study area. However, the existing reservoirs are very large compared to the annual volume discharged by the study area. Evidently, there is a direct hydraulic connection between the Neogene Complex and the underlying formations through a truncation of the Rus window on the top of the Ghawar structure. The truncation of the Rus Window allows water to flow up from the Umm-Er-Radhuma to the Neogene (El Khatib, 1980).

Hydraulic properties of the Neogene formation in the area show that the transmissivity coefficient varies between 0.0007 and 0.04 m^2/second with an average of 0.02 m^2 /second, and storage coefficient is about 0.0002. The Neogene formation is the main aquifer feeding the natural springs in the area (Othman, 1983). The total annual discharge of the natural springs was estimated at 208.8 MCM in 1982. It was used mainly for agricultural purposes (Al-Taher, 1987). The total annual recharge via rainfall and run-off was estimated at 328 MCM (Othman, 1983).

The Dammam Formation

The Dammam formation includes five members. Two of them are water-bearing formations: the Khobar and the Alat (Othman, 1983). The Khobar member is a limestone formation. It is the second most extensive formation in the area. The general flow pattern of the Khobar formation is south-west to north-east. The hydraulic gradient increases eastward from Hufuf-Abqaiq, reflecting low transmissivity of this aquifer between Hufuf and the Gulf coastline. The Khobar Limestone member has been severely truncated on the top of the Ghawar anticline where there are horizontal and vertical connections between Khobar and Umm-Er-Radhuma formations from below and Neogene complex from above.

The Alat Limestone formation is a thin layer with very low productivity. It cannot be considered by itself a generalized aquifer. However, it has good hydraulic properties when it is connected to form part of the underlying Khobar formation. The Khobar-Alat formation forms part of the Dammam formation. It consists of two water bearing limestone units which are partially separated by a thin shale unit (El Khatib, 1980).

Hydraulic properties of the Dammam formation (Khobar-Alat) in the study area show that the average transmissivity coefficient is 0.02035 m^2/second, and the average storage coefficient is 0.0002. The annual discharge was estimated to be eight MCM which is mostly used for potable and agricultural purposes. On the other hand, annual recharge of the Dammam formation was estimated at 1601 MCM, most of which is derived from the upward leakage of the Umm-Er-Radhuma formation (Othman, 1983).

Umm-Er-Radhuma Formation (UER)

The Umm-Er-Radhuma formation is a powerful generalized aquifer which occurs throughout the study area. It is a highly productive aquifer especially at the western outcrop and on the Ghawar structure. The general water flow within the formation is south-west to north-east. The water flow, however, is interrupted by the Ghawar structure where the flow pattern is south to north. The main intake areas of the Umm-Er-Radhuma formation are:i) the south-western outcrops and the southern zone; and ii) the Ghawar structure where a recharge occurs from or through the overlying aquifers by vertical leakage. The vertical connection takes place mainly in the Dammam differential truncating zone on the top of the Ghawar anticline. There is a relationship between the aquifers supplying water to Al-Hassa area and interrelation of infiltration through the Neogene layer to the Umm-Er-Radhuma water table (El Khatib, 1980).

PREVIOUS STUDIES

I. LITERATURE REVIEW

The problem of water use in Saudi Arabia requires urgent solutions that solve the problem or mitigate its severity. Considerable attention has been given to the use of non-renewable groundwater reserves in the agricultural sector. Geological and hydrological models were developed to study the use and potential development of groundwater in Saudi Arabia. These studies are summarized in sequence as follows:

Beraithen (1982) developed a groundwater management model to measure the optimal pumping rate from the Minjur aquifer in Riyadh region. Two finite-difference models were used to simulate the steady state calibration of the Minjur aquifer. These were the Trescot and McDonald models.

Al-Bassam (1983) developed a three-dimensional finite-difference model to simulate the steady state calibration of Umm-Er-Radhuma aquifer in the Haradh Wellfield study area. A multi-aquifer model was used to measure the responsive change of the piezometric heads to different pumping rates and times in the study area. The decline of head was predicted for 100 years.

Al-Ghamisi (1988) developed a methodology to determine the optimal usage of a large-scale formation. A groundwater management model was formulated and applied to determine the optimal pumping rate from the Saq formation in Gassim region in northern-central Saudi Arabia. The general head boundaries technique was used to successfully model the Saq formation in the study area. Partial differential equations were utilized to efficiently link the response of the Saq formation to different pumping activities. The objective function of the optimal management model was to maximize the volume of pumped water in the region.

Al-layla et al., (1992) developed a regional simulation model to study the consequences of future development in the Dammam aquifer in Eastern Saudi Arabia. Steady state calibration and transient simulations were developed to determine the regional distribution of transmissivity, storativity, and vertical leakance rate. Several development scenarios were formulated and tested to determine the impact of future regional development on the Dammam aquifer between 1985 to 2000.

Al-Tokhais (1992) studied the non-renewable groundwater resources in Saudi Arabia. Reducing the rate of extraction from the aquifers, extending the expected life of the groundwater reserves, and maintaining the agricultural development in the Kingdom were the main goals of the study. Three groundwater management strategies were proposed to achieve the proposed goals. Drilling wells with adequate spacing in rows parallel to the aquifer outcrop was found to be the best strategy.

Al-Assar (1992) developed a two-dimensional model to study the water flow in the Umm-Er-Radhuma aquifer for the Al-Sharqiya agricultural company in Eastern Saudi Arabia. The model was used to predict the hydraulic response of the aquifer over a seven year period under various management alternatives.

Al-Dakheel (1992) developed a multi-means methodology to manage the use of groundwater in Riyadh in central Saudi Arabia. The objectives of the study were to secure a future groundwater supply, improve water quality, and minimize water treatment cost. The basic means to achieve the proposed objectives were water transfer, conservation, and water banking through artificial recharge. Three models were developed to measure changes in the quantity and quality of water: a groundwater flow model, a solute transport model, and a linear programming model.

Al-Sheikh (1995) developed a two-stage model to determine the connection between agricultural policies and optimal allocation of water resources in Riyadh area in central Saudi Arabia. The model measured the impact of government intervention on the use of water over time and its allocation between competing uses. In the first stage, he developed a detailed agricultural sector model to measure: i)the impact of the current price policy on the economics of water use at the farm level; and ii)the potential economic loss due to inefficient use of water. In the second stage, he developed a dynamic optimal control model of the water sector to account for: i)the pumping costs associated with different levels of water quantity and location; and ii)the presence of a backstop technology.

The water issue in Saudi Arabia has also been studied from a national water balance approach. These studies are summarized below: *Fathi et al. (1977)* reported that some countries have examined the economic feasibility of using seawater desalination in agricultural operations. To date, the high cost of the desalinated water makes its use in agricultural operations economically infeasible. However, they reported that the solar energy methods such as distillation and a newly proposed freezing method were found promising.

Al-Mudaiheen (1985) analyzed water resources in Riyadh to determine their advantages in meeting increasing water demand. The main focus of the study was the development of the deep groundwater aquifers including the Minjur and the Wasia as well as the shallow aquifers such as the Wadi Hanifah and the Wadi Nisah. The study also focused on the potential use of desalinated sea water and treated wasted water instead of groundwater.

Abu Rizaiza and Allam (1989) described the existing water resources in Saudi Arabia and discussed the major problems in water uses and their policy implications in light of the national water balance. Abu Rizaiza and Allam stated that under the most optimistic conditions of groundwater resources, the depletion of groundwater resources will occur within the next few decades.

Al-Ibrahim (1990) delineated the water supply and demand picture in Saudi Arabia and concluded that a water crisis is impending if the water demand-supply situation were not brought into balance. Al-Ibrahim stated that the depletion of groundwater resources may occur by the year 2047 or sooner.

Abdulrazzak and Khan (1990) examined suitable domestic water conservation measures in Saudi Arabia and their implementation in terms of their monetary and water saving potential. The suggested measures include: installing water saving devices, educating the public, and reusing wastewater. Implementing these measures would decrease the rate of water consumption by about 55 percent and reduce the domestic cost by 7 to 9 Riyals per cubic meter.

Al-Zahrani and Mansour (1992) analyzed the national water balance from the demand management point of view and examined the possibilities of a plan to extend water conservation measures in Saudi Arabia. The findings of the study implied the possibility of reducing the current level of water consumption by about 32 percent through the adoption of water conservation measures.

The optimal allocation of irrigation water in agriculture has been addressed in several studies. The potential for increased net farm income from limited resources, and with improved irrigation efficiency has been examined in different parts of Saudi Arabia. *Humaidan (1980)* developed policies and management guidelines for maximizing net returns to scarce agricultural resources in Al-Hassa irrigation and drainage project. The author developed cost and return budgets for a number of crops. A regional linear programming model was then used to determine the maximum net farm income from the limited resources. *Battal (1986)* developed a linear programming model to allocate the limited water resources in Al-Kharj district-Saudi Arabia for a single irrigation season.

Al-Taher (1987) assessed field irrigation efficiency under traditional, intermediate, and modern irrigation systems and studied the relationship between irrigation and agricultural production efficiencies in Al-Hassa area. The study found the efficiency of modern irrigation systems to be the highest and that of traditional irrigation systems to be the lowest.

Bahanshal (1989) studied the connection between water resource use and the current agricultural policies in Saudi Arabia, particularly in the wheat industry. The study showed the conflict between achieving both water and food security goals. The study stated that educating the public especially in agriculture about how to conserve water through adopting better technical and management practices would help to mitigate the water emergency in the Kingdom.

Several studies have been conducted around the world on the use of water resources. *Burt (1964)* examined the optimal temporal allocation of a single non-renewable or partially renewable water resource. *Hanson (1966)* examined the economic and physical consequences of groundwater mining for irrigation.

Lewis (1969) examined the economic consequences of irrigation development under optimum and less than optimum water supply conditions. A priority in water use among crops was developed when the water supply is limited. The study also compared the net return of irrigating different numbers of acres using reservoir and direct diversion systems.

Burt (1974) presented a general model for the optimal inter-temporal allocation of groundwater from several hydrologically interconnected aquifers and economically analyzed the interaction between the timing of surface water development and the location at which water is delivered with the inter-temporal allocation of groundwater stocks.

Stoecker et al., (1985) developed a linear-dynamic programming model to measure the economic benefits of irrigation system development over a depleting aquifer in Texas. The study considered management issues such as configuration of distribution system, drilling policy, area developed for irrigation, and crop production. *Rempe (1985)* stated that irrigation efficiency could be improved through many means, yet irrigation scheduling is the most reliable.

II. POTENTIAL CONTRIBUTION

The review of literature indicates several studies have been conducted to study the emergence situation of water resources and its connection to the agricultural sector in Saudi Arabia. Some studies developed linear programming models to determine the optimal water use in agriculture (*Humaidan, 1980; Battal, 1986*). Other studies developed groundwater flow models to study the consequences of future development in the regional groundwater aquifers (*Berathen, 1982; Al-Bassam, 1983; Al-Tokhais, 1992; Al-Assar, 1992; Al-Dakheel, 1992*). Still other studies developed linear-groundwater models to determine the optimal pumping policy and groundwater use (*Al-Ghamisi, 1988; Al-layla et al., 1992; Al-Sheikh, 1995*).

None of these studies have developed a comprehensive model which simultaneously determines: i) the optimal use of water in agriculture which maximizes net social benefits; ii) the consequences of the future development in the groundwater aquifer, and iii)the optimal irrigation development decisions.

The methodology developed in this dissertation is a comprehensive multi-model approach that uses three models: a linear programming model, a groundwater flow model, and a dynamic programming model. This comprehensive multi-model is used to determine the optimal temporal allocation of groundwater and other limiting resources in agriculture which maximizes the discounted net social benefits associated with three irrigation systems: surface system, sprinkler system, and trickle system.

The questions addressed and answered by this study include: How to improve the efficiency of using groundwater in agriculture? What are the efficient crop mixes that comply with the national scarce resources and subject to the optimal long-term use of non-renewable groundwater resources? What is the most efficient irrigation system in agriculture? What are the most efficient water conservation practices that could be developed and applied to reduce water loss in the agricultural sector? What is the optimal allocation of groundwater between current and future use? What are the optimal long-term pumping scenarios? What are the optimal farm management and irrigation development decisions in the long-term?

CHAPTER III

PLAN OF THE STUDY

OPTIMAL EXTRACTION OF A NON-RENEWABLE RESOURCE

Non-renewable resources including groundwater are formed through geological processes that take millions of years. A purely non-renewable groundwater resource is a finite stock which once extracted cannot be replaced. A unit of groundwater extracted at present time reduces the future stock. The decision maker and society should use the finite reserve in such a way that discounted net social benefits (NSB) are maximized. Net social benefits were defined by *Samuelson (1952)* as being equal to the sum of consumer surplus (CS) and producer surplus (PS). Maximizing CS and PS is equivalent to finding a competitive equilibrium.

The optimal extraction path of a non-renewable or partially renewable resource that maximizes the NSB is derived mathematically by *Hartwick and Olewiler (1986)*. An inverse linear demand function that shows the willingness to pay for resource Q_t in year y is,

$$P_t = d_t + dd_t\ Q_t \qquad (1)$$

where,

d_t = intercept of the inverse demand function that states the willingness to pay for the resource.

dd_t = the slope of the inverse demand function which states the inverse relation between quantity demanded of the resource and its price.

Q_t = quantity demanded of the resource.

The marginal extraction cost for the groundwater resource for each year could be written as,

$$MC_t = c_t + cc_t\, Q_t \tag{2}$$

The annual net social benefits in terms of consumer-producer surplus can be written as the total area under the demand curve less the area under the supply curve as,

$$CPS_t^y = \int_0^{Q_t} (d_t + dd_t Q_t)\, dQ_t - \int_0^{Q_t} (c_t + cc_t Q_t)\, dQ_t \tag{3}$$

$$CPS_t^y = (d_t + 0.5 dd_t Q_t^2) - (c_t + 0.5 cc_t Q_t^2) \tag{4}$$

where CPS^y_t is the NSB or the sum of consumer and producer surplus in year t.

If Q_t were infinite, annual consumer and producer surplus is maximized by taking the derivative of CPS^y_t with respect to Q_t as,

$$\frac{\partial CPS_t^y}{\partial Q_t} = d_t + dd_t Q_t - c_t - cc_t Q_t = 0 \text{ ,for all t} \tag{5}$$

$$Q_t = \frac{c_t - d_t}{dd_t - cc_t} \tag{6}$$

If the resource is non-renewable or partially renewable, the problem of finding the amount of Q_t that maximizes the discounted NSB can be expressed as a constrained optimization problem,

$$MAX\ L(Q_t, TS_t, \lambda_t) = \sum_{t=1}^{T} \frac{(d_t + 0.5 dd_t Q_t^2) - (c_t + 0.5 cc_t Q_t^2)}{(1+i)^t} + \sum_{t=1}^{T} \lambda_t (TS_t + TR_t - Q_t - TS_{t+1}) \tag{7}$$

where,

TS_t = total groundwater reserve in the beginning of time t.

TR_t = total recharge to the groundwater reserve in time t, which is assumed constant and exogenous.

Q_t = total discharge from the groundwater reserve in time t.

λ_t = a langrangian multiplier which is equal to the value of one more unit of the resource in year t.

t = 1, 2,..., T time period.

i = the discount rate.

The optimal extraction quantity (Q_t) is maximized by taking the partial derivatives of equation (7) with respect to Q_t, TS_t, and λ_t,

$$\frac{\partial L}{\partial Q_t} = \frac{(d_t + dd_t Q_t) - (c_t - cc_t Q_t)}{(1+i)^t} - \lambda_t = 0 \tag{8}$$

$$\frac{\partial L}{\partial TS_t} = \lambda_t - \lambda_{t-1} = 0 \tag{9}$$

$$\frac{\partial L}{\partial Q_t} = TS_t + TR_t - Q_t - TS_{t+1} = 0 \tag{10}$$

Equation 9 states that λ is constant for all periods. If the value of λ were known, then the optimal Q_t is,

$$Q_t = \frac{(\lambda_t (1+i)^t - d_t + c_t)}{(dd_t - cc_t)} \tag{11}$$

That is, if λ_t were constant for all periods, the optimal value of Q_t would be declining overtime, while the expected price paid for Q_t would be rising. The long-run equilibrium or the steady state equilibrium for the Q_t will be at the point of economic exhaustion if recharge is equal to zero. If the recharge is positive, the long-run equilibrium may be reached where $Q_t = TR_t$.

A simple method to solve for the optimal Q_t is to use the iteration process in which the initial value of λ_t is specified. The amount of Q_t* each year is then given as,

$$Q_t = \frac{(\lambda_t (1+i)^t - d_t + c_t)}{(dd_t - cc_t)} \tag{12}$$

The present value of the NSB for each year is readily calculated and summed over the planning horizon as,

$$NSB = \sum_{t=1}^{T} \frac{(d_t + dd_t Q_t) - (c_t - cc_t Q_t)}{(1+i)^t} \tag{13}$$

Another value of λ_t can be specified and the NSB is recalculated. The second value of the discounted NSB is compared with the first. The value of λ_t is revised and the process is repeated until the discounted NSB has reached a maximum.

THE MATHEMATICAL MODEL

The overall research problem for the representative study area is to determine the optimal temporal development and utilization of groundwater. This requires a simultaneous determination of the optimal number of irrigation systems to be purchased, the land area to be developed, the number of irrigation wells to be drilled, the amount of water to be used annually, the mix of crops to be grown annually, and the amount and time of irrigation for each crop. This is indeed a nonlinear multi-period mixed integer programming model.

Solving this problem as one single large problem would require substantial computer resources. Instead a Linear-Dynamic Programming (LDP) approach will be used which will allow the overall problem to be decomposed and solved in steps (Stoecker et al., 1985). The LDP method contains three interrelated steps: the first step uses parametric linear programming (PLP); the second step uses a three-dimensional finite-difference groundwater model (GF); and the third step uses discrete dynamic programming (DP) to actually solve the problem.

The technique used in the third step listed above is discrete, deterministic, finite stage, backward recursive dynamic programming. Assume there are N periods or years in the planning horizon. *Nemhauser (1964)* showed that DP could be used in the decomposition of block diagonal programming problems as an alternative to the LP decomposition principle of *Dantzig and Wolfe*. That is the problem can be partitioned into N+1 subsets such that N subsets (or stages) form mutual independent systems while the (N+1) subset contains equations or constraints which form a common linkage among variables in the above N subsets.

Accordingly, the decision variables in the current problem can be divided into two groups. The first group contains those variables whose level in one period affects NSB in that period but has no influence on NSB in any subsequent period. The second set contains those variables whose levels in one period do affect the value of NSB in later periods. The variables in the second set are: i) the total amount of water used in a year; ii) the number of irrigation wells which are drilled; and iii) the investment in irrigation systems. These latter variables will be decision variables in the DP model. The variables in the first set are far more numerous and include, the area planted to each crop, the amount and timing of irrigation on each crop, the amount of labor hired, the amount of each crop to import or export.

Note that in the problem in equation (4), if the maximum quantity that could be used in each year were specified at Q_t*, the decision maker only has to maximize NSB in each year subject to the constraint that Qt is less than or equal to Qm_t. In the description which follows, parametric linear programming was used to determine the maximum NSB which can be obtained from the study area subject to a maximum: i) level of annual water use; ii) number of irrigation wells; and iii) land area developed for irrigation. These will be state variables in the DP model.

The DP model can be represented only in terms of the value of the PLP objective function for each combination of state variables. The levels of the decision variables in set 1 are not required for the final step. However, the solution of one very large programming model is replaced by the solution of many smaller programming models. If for each year, there were five possible levels of annual water use, five possible irrigation system configurations, and five numbers of wells this requires 125 LP solutions for each of the N stages. The transition equations for each of the variables must also be derived.

A schematic diagram showing the connections among the interrelated models in the study is illustrated in *Figure V*. The steps on the left side of *Figure V* show the steps related to constructing and solving the PLP model. The steps on the right side of *Figure V* show the steps related to constructing and solving the GF model. In this study the overall problem was solved in steps in which the results of each step were used as inputs in each succeeding step. Pumping drawdown models developed by *Dawson and Istok (1991)* were used to estimate pumping drawdown of the Umm-Er-Radhuma aquifer, which is the main supplier of the regional aquifers, in response to different withdrawal rates over time. Multiple regression equations were developed to empirically relate the estimated pumping drawdown to the number of pumping days and discharge from the aquifer. The developed regression equations were then used in a pumping cost model developed by *Stoecker (1994)* to calculate the cost of pumping at various conditions of the aquifer (confined VS. unconfined) and number of wells. The results of the pumping cost model provided a series of outputs (pump efficiency, pumping drawdown, pumping cost) that could

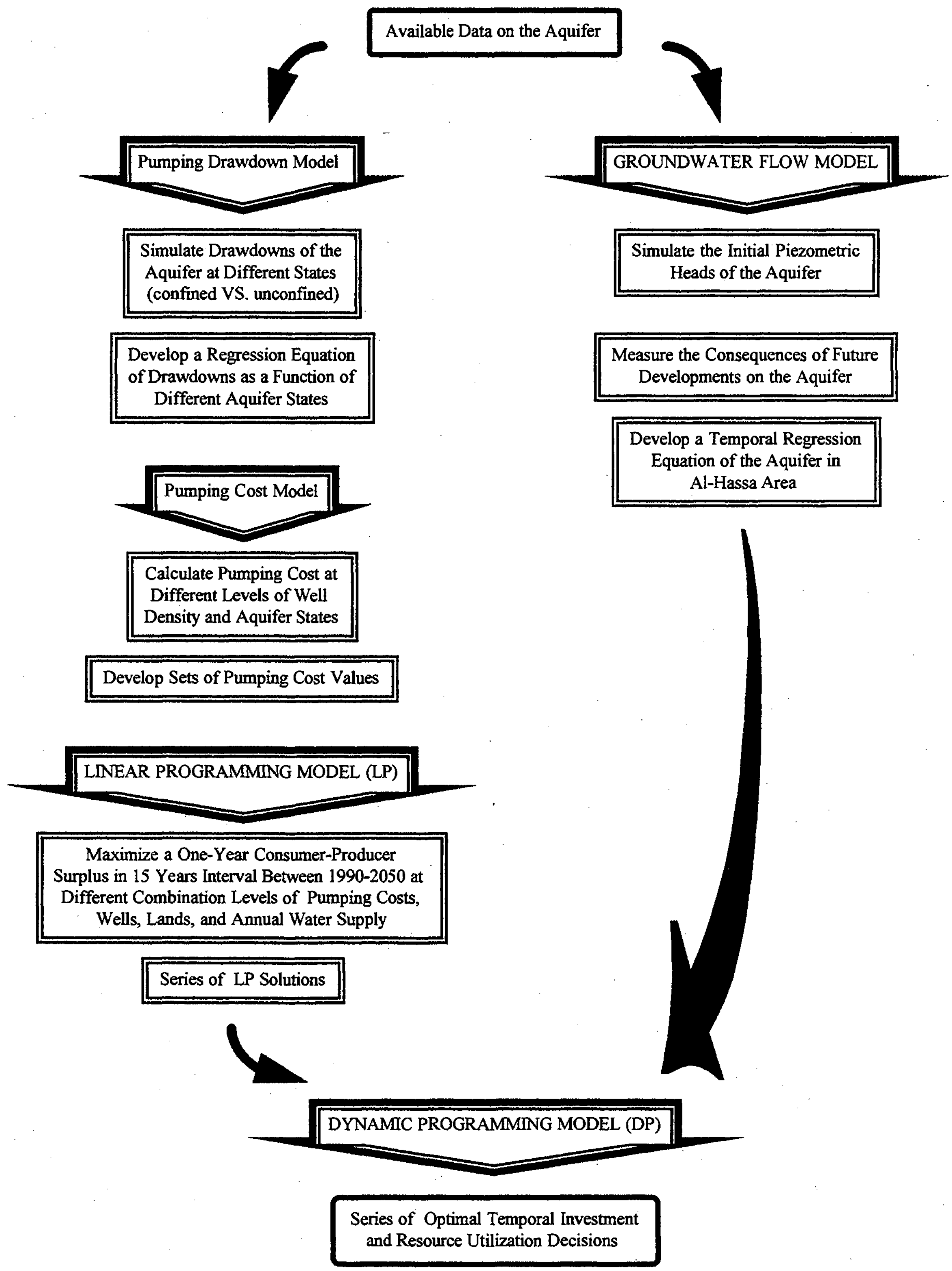


FIGURE V. A SCHEMATIC DIAGRAM SHOWING THE CONNECTIONS BETWEEN MODELS USED IN THE STUDY be used as input in the parametric linear programming model (PLP).

Parametric programming was used to determine a series of one-year solutions each of which represented the maximum net social benefits that could be obtained from each unique combination of: i)depth to the static water table; ii)irrigated area; iii)number of irrigation wells; and iv)maximum annual water use. The PLP solutions were obtained with projected demand for each 15 year interval between the year 1990 and 2050. The LP solutions provided the first series of inputs to the dynamic programming model (DP).

In addition to the maximized NSB solutions provided by the PLP model, the DP model requires another set of inputs regarding the regional aquifers (piezometric head). A groundwater flow model (GF) developed by *McDonald and Harbaugh (1980)* was used to estimate the change in the piezometric heads in response to different levels of withdrawals from the study area over a 100 year time period. A multiple regression equation was developed to empirically relate the change in the piezometric heads of the regional aquifers to different discharge rates from the study area and to the changes in the piezometric head in the Rus window area over time. The Rus window area is located to the west of the study area. It plays an essential role in connecting the regional aquifer system. The resulting multiple regression equations represented the second set of inputs to the DP model.

The DP model developed by *Stoecker (1995)* was the final step in the study. It was used to determine the optimal investment decisions concerning number of irrigation wells drilled, irrigated areas developed, and annual water use that maximized the discounted net social benefits.

DYNAMIC PROGRAMMING MODEL (DP)

The DP step determines the optimal allocation of groundwater over time that yields the highest net present value (NPV). Decisions are made at the beginning of each stage assuming certainty for both the resulting NPV and the appropriate changes in the states. The stages are equally spaced along the planning horizon (Stoecker et al. 1985).

The DP step is divided into N decision stages (years). Each stage is associated with a number of states. The state variables associated with each stage include: number of existing wells; land area irrigated; and the remaining water supply in the aquifer. The decision variables at each stage (year) include: increasing or decreasing the number of drilled irrigation wells, increasing or decreasing the area developed for irrigation, increasing or decreasing the size of irrigation system, and determining the amount of groundwater used. The solution technique of the DP step starts by determining the optimal policy for each state at the terminal stage.

A recursive DP formula which introduces the maximum net present value at each stage of returns as shown by Stoecker et al. (1985) is:

$$R_n(V_n) = max[R_n(V_n, D_n) + zf_{n+1}(t_n(V_n, d_n))]$$

where,

$R_n(V_n)$ = maximum NPV at stage n of returns.

$R_n(V_n, D_n)$ = series of current returns at stage n for a producer operating at V_n using all feasible sets of D_n.

$zf_{n+1}(t_n(V_n, d_n))$ = the maximum NPV of returns in all future stages given that decision d_n is made with state V_n.

z = 1/(1+ r) where r is the periodic rate of discount.

D_n = set of decision variables.

V_n = set of state variables.

n = 1, 2,...,N-1.

The output of this step provides a series of optimal management and irrigation development decisions over a planning horizon of n periods.

PARAMETRIC LINEAR PROGRAMMING MODEL

The structure of any agricultural sector model comprises essentially five elements. These elements were mentioned by *Hazell and Norton (1986)* as follows: i)a description of the economic behavior of producers such as motives of profit maximization and risk aversion; ii)a description of the available production functions and technologies to producers; iii) a definition of the available resource endowments; iv) a specification of the accessible market environment to producers such as perfect competition and monopoly; and v) a specification of the sectoral policy environment such as subsidies, import tariffs, and quotas. These elements potentially delineate the agricultural sector as an economic unit.

Marketing Structure

The market is visualized in this study as having two supply regions. Both regions compete to satisfy the national demand of a given commodity. These production regions represent: i) supply from the study area; and ii) supply from outside the study area or the rest of the nation. Supply from the study area, which is shown as the difference between the S_o and $S_0 + S_h$ curves in *Figure VI*, will be determined in the production activity section of the model. The supply from the rest of the nation will be represented by a set of linear supply curves and the assumption the market is competitive so that producers outside the study area produce where price = marginal cost.

It was shown above in equation (4) that the objective function which maximizes the net social benefits (NSB) for a model with linear demand and supply equations is quadratic (non-linear) in form. The linear approximation techniques

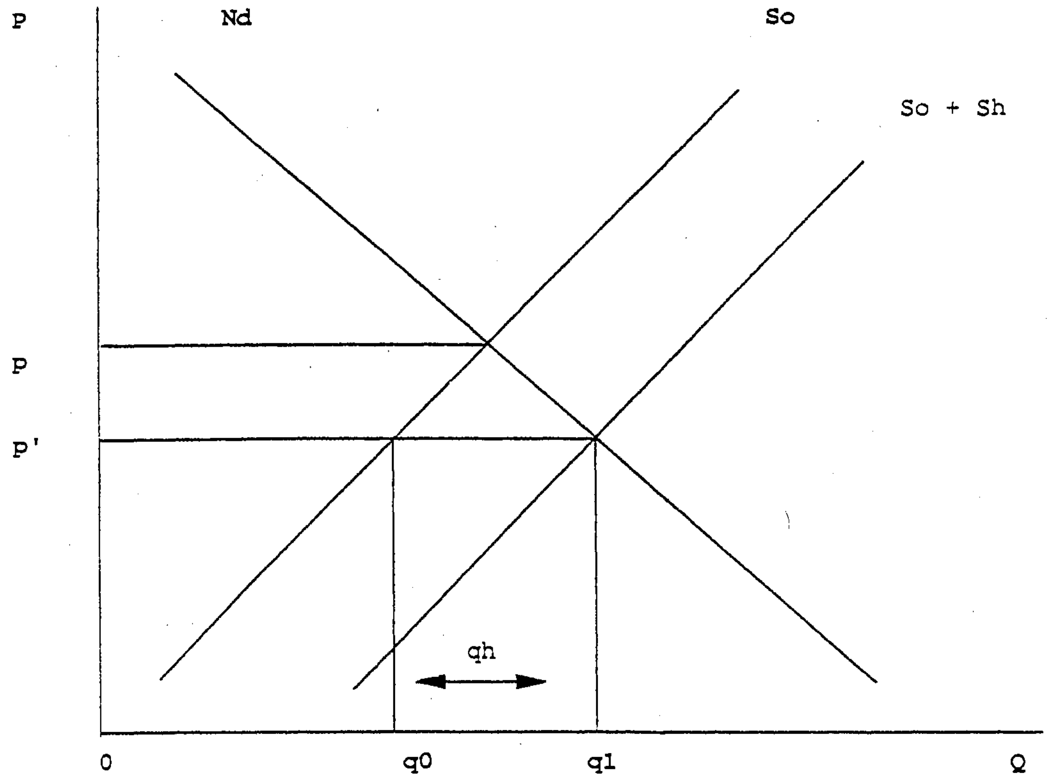


FIGURE VI. NO TRADE MARKET STRUCTURE

described by *Hazel and Norton (1986)* could have been used to linearize the NSB function related to the national demand and the supply from the rest of the nation. However, the technique described below which uses segmented excess demand or supply equations allowed the same accuracy of approximation from a smaller programming model.

Figure VI shows that in the no trade case (or for a commodity which is traditionally imported), the quantity produced from the study area at price p′ represents the difference between the quantity which would be supplied from outside the study area (q_o) and the total quantity demanded in the market (q_1). At p, the quantity demanded for production from the study area is zero. In mathematical notation, an excess demand equation for the case shown in *Figure VI* is derived below as follows:

The national demand function for a given commodity can be written in price flexibility form as,

$$P_{jn} = d_{jn} + dd_{jn}\ Q^d_{jn} \tag{14}$$

It can also be expressed so the quantity demanded is a function of commodity price,

$$Q^d_{jn} = -\ (d_{jn}/dd_{jn})\ +\ (P_{jn}/dd_{jn}) \tag{15}$$

The linear demand function can be derived from the following information: i)the initial crop price; ii)the initial crop quantity; and iii) the own price elasticity.

The marginal cost or minimum price at which producers from outside the study area (MC_{jo}) would produce each level of output is,

$$MC_{jo} = c_{jo} + cc_{jo}\ Q^s{}_{jo} \qquad (16)$$

which can be written as,

$$Q^s{}_{jo} = -\ (c_{jo}/cc_{jo}) + (Mc_{jn}/cc_{jo}) \qquad (17)$$

In equilibrium, the quantity supplied by both regions occurs at a level when the marginal cost is equal to the market price for each commodity,

$$Mc_{jh} = MC_{jo} = P_{jn} \qquad (18)$$

which means that the sum of production from both regions is equal to the total quantity demanded at the national level,

$$Q^d{}_{jn} = Q^s{}_{jh} + Q^s{}_{jo} \qquad (19)$$

if the market is at equilibrium at price P_{jn}.

The quantity produced in the study area is the difference between the quantity demanded at the national level and the quantity supplied from outside the study area,

$$Q^s{}_{jh} = Q^d{}_{jn} - Q^s{}_{jo} \qquad (20)$$

Substituting equations (15) and (17) into equation (20), supply from the study area is,

$$\begin{aligned} Q^s{}_{jh} &= -\ (d_{jn}/dd_{jn}) + (P_{jn}/dd_{jn}) + (c_{jo}/cc_{jo}) - (Mc_{jn}/cc_{jo}) \\ &= -\ ((d_{jn}/dd_{jn}) - (c_{jo}/cc_{jo})) + ((1/dd_{jn}) - (1/cc_{jo}))\,P_{jn} \qquad (21) \end{aligned}$$

which can be expressed in terms of price flexibility form as,

$$P_{jn} = d'_o - dd'\ Q^s{}_{jh} \qquad (22)$$

The excess demand function of a given commodity, which represents the difference between national demand and supply from outside the study area, is linearized and used in the linear programming model (LP) by defining selling activities. Each selling activity is set with an upper bound.

Figure VII illustrates the linearized excess demand quantities in relation to price level. At p_1, the difference between quantity demanded at the national level and supplied from outside the study area is equal to qh_1 which is produced in the study area. At a lower price level of p_2, the excess demand quantity would be the difference between q_{j2} and p_1 which is equal to qh_2. *Figure VII* also shows entries of the selling activities along with their upper bounds for a given commodity.

Given the cost $(-c_{jh})$, the production from the study area $(-y_{jh})$ at least balances out the excess demand resulting from the difference between the quantity demanded at the national level and the quantity supplied from outside the study area at the a *priori* specified price (p_{ji}). Each excess demand function is set at an upper bound equal to Qh_{ji}.

The basic structure of the agricultural sector in Al-Hassa study area includes the following elements: i) an objective function; ii) resource constraints; iii) commodity balances; and iv) trade balances. Extensive use is made of excess demand and excess supply segment variables. The production section of the model represents average total production of traditional and specialized farms in Al-Hassa

Entries of the Selling Activities

Production Activities	Selling Activities					
Supply from the study area	Excess Demand 1	Excess Demand 2	...	Excess Demand i	RHS	
$-c_{jh}$	p_{j1}	p_{j2}	...	p_{ji}		
$-y_{jh}$	1	1	...	1	$\leq$	0.0
	1				$\leq$	Qh_{j1}
		1			$\leq$	Qh_{j2}
			...		$\leq$	...
				1	$\leq$	Qh_{ji}

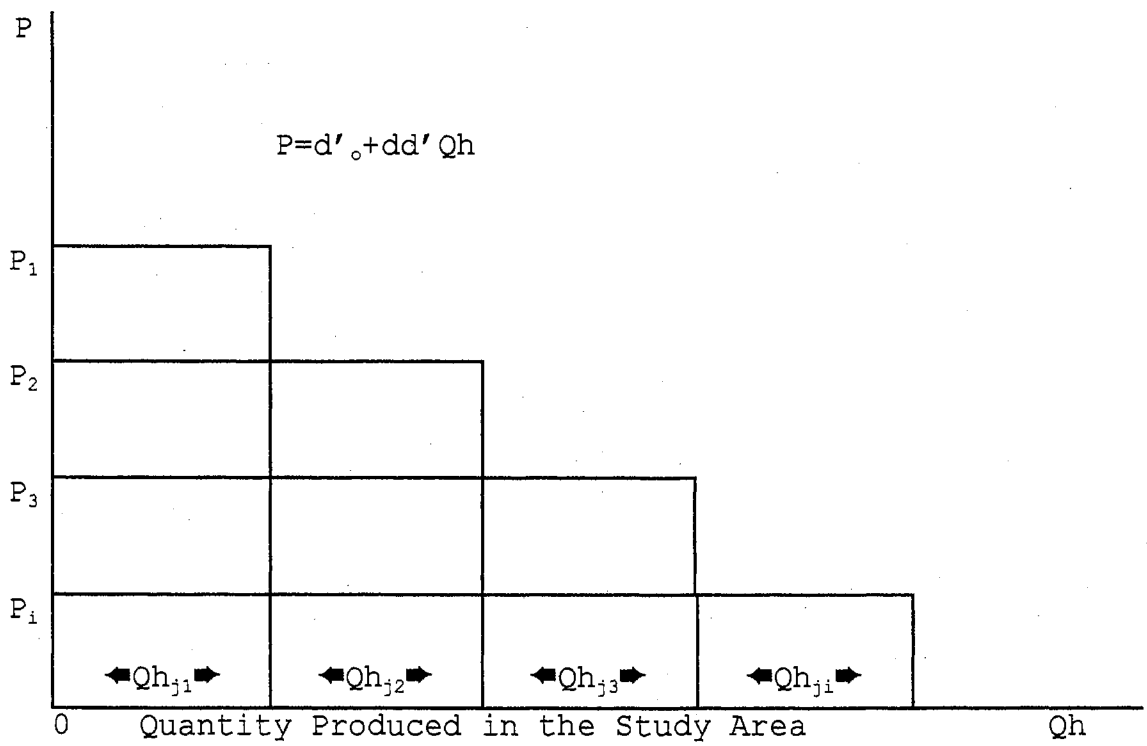


FIGURE VII. EXCESS NATIONAL DEMAND FUNCTION FOR PRODUCTION FROM THE STUDY AREA

study area, which will be defined throughout the remaining chapters as *the study area*. A portion of the initial LP tableau of the crop farming sector in Al-Hassa study area is presented in *Table IX*. The tableau illustrates the structure of winter tomatoes and wheat activities.

Objective Function

The objective function of the LP model for a given s^{th} irrigation system is to determine the optimal one-year farm plan which includes the allocation of groundwater and the other limited resources among farming crops. The model maximizes the annual consumer and producer surplus associated with various levels of: i)pumping costs; ii)potential arable land; iii)drilled wells; and iv)annual water use.

$$Z^{ys}_{plaw} = \sum_{j=1}^{J} F(W^y_j) - C^{ys}_{jh} X^{ys}_{jh} - I^y_{jn} + E^y_{jn} - LC^y$$

where,

Z^{ys}_{plaw} = the maximized producer and consumer surplus in terms of Saudi Riyals (SR) in year (y), given the level of pumping cost (p), the hectares of irrigated area (l), the annual water use (a), and the number of drilled wells (w).

$F(W^y_j)$ = the welfare function which measures the area under excess demand equation for the j^{th} crop in year y.

C^{ys}_{jh} = average cost for j^{th} crop with irrigation system s in the study area (h) in year y, measured in Riyals per ton.

X^{ys}_{jh} = average j^{th} crop's production in the study area with irrigation system s in year y, measured in tons per hectare.

I^y_{jn} = net national import from j^{th} crop in year y.

E^y_{jn} = net national export from j^{th} crop in year y.

TABLE IX

A PORTION OF THE INITIAL TABLEAU, SURFACE IRRIGATION SYSTEM.

Rows	Maximize	RHS	WWH...	WTM...	WWHES1..	WWHES6..	WTMED1..	WTMED6..	WWHEV...	WTMIV...	H.Labor	F.Labor
OBJ.Fn.			-6392..	-28018..	-1554..	-2000...	712...	890...	2018...	-860...	-7	-5
MWSUP.1	≤	436	0.12...	...								
⇓	≤	...	...	...								
MWSUP.24	≤	676	0.12...	0.10...								
LAND 1	≤	8000	1...									
⇓	≤	...	...	...								
LAND 12	≤	8000	1...	1...								
H.Labor	≤	0	136...	875...							-1	-1
F.Labor	≤	12074267										1
AWSupply	≤	23465	0.91...	1.79...								
WWHACR	≤	0	-4.11...		-1...	-1...			1...			
WTMACR	≤	0		-39.36..			1...	1...		-1...		
WWHES.1	≤	1791227										
⇓	≤	...	...	...								
WWHES.6	≤	7503										
WTMED.1	≤	5852										
⇓	≤	...										
WTMED.6	≤	79416										
⇓	≤	...										
WWHNEQ	≤	1881144							1...			
WTMNIQ	≤	68616								1...		

OBJ.Fn = objective function; MWSUP.1 = monthly water supply in 1-15 Jan.; MWSUP.24 = monthly water supply in 16-31 Dec.; Land 1 = land available in Jan.; Land 12 = land available in Dec.; H.Labor = hired labor; F.Labor = family labor; WWHACR = wheat account raw; WTMACR = winter tomato account raw; WWHES.1 = wheat 1st excess supply level; WTMED.6 = winter tomato 6th excess demand level; WWHNEQ =wheat net export quantity; WTMNIQ = winter tomato net import quantity; IRRGREQT = total irrigation requirements; WWHEV = wheat export value; WTMIV = winter tomato import value.

LC^y = labor cost in year y, measured in Riyals per hour.

i = 1, 2,..., I constraints.

j = 1, 2,..., J crops.

y = 1, 2,..., Y years (stages).

t = 1, 2,..., 12 months.

w = 1, 2,..., W wells.

s = 1, 2, 3 irrigation systems.

q = 1, 2,..., Q aquifer states.

p = 1, 2,..., P pumping cost levels.

a = 1, 2,..., A annual water use.

Resource Constraints

Resource constraints ensure that the amount of the limited resources used in the production process does not exceed what is available. This study focuses on three limited resources: water supply; arable land; and skilled labor.

Water supply constraint is presented in two forms: i)a bi-weekly water supply $M(w^y,m^y)$;and ii)annual water supply $WV(q^y)$. The bi-weekly constraint insures that irrigation requirements for all crops do not exceed the bi-weekly water supply. The quantity of water available to crops in each two week period was based on the output of each well times the number of wells and the hours of continuous operation. The annual water supply constraint ensures annual irrigation requirements for all crops do not exceed a specific quantity of water.

The use of *arable land* is modeled on a monthly basis because: i)each crop in the model has a different growth period from planting to harvesting, and ii) climatic conditions in the study area often allow the production of more than one crop from the same land in one year (Humaidan, 1980). The arable land is measured in hectares (ha).

Skilled labor is available in two forms: i)family labor at a reservation wage rate of 5 Saudi Riyals per hour (SR/hr); and ii)hired labor at a wage rate of 7 Saudi Riyals per hour (SR/hr).

The above resource constraints are illustrated algebraically as follows:

$$\sum_j \quad a^y_{ijh} \quad X^y_{jh} \quad \leq \quad b^y_{ih}$$

$$\sum_j \quad a_{jth} \quad X^y_{jh} \quad \leq \quad M_h(w^y_h, m^y_h)$$

$$\sum_t \sum_j \quad a_{jth} \quad X^y_{jh} \quad \leq \quad WV_h(q^y_h)$$

where,

a^y_{ijh} = an input-output coefficient that states the amount of i^{th} limited resource required to produce one hectare of j^{th} crop in the study area (h) in year y.

b^y_{ih} = total amount of the i^{th} limited resource available in the study area (h) in year y.

a_{jth} = amount of irrigation required for the j^{th} crop in the study area (h) in bi-weekly time period t.

$WV_h(q^y_h)$ = annual water supply given pumping level q in the study area (h) in year y.

$M_h(w^y_h, m^y_h)$ = maximum bi-weekly water supply of w wells from an aquifer with m meters to the water table in the study area (h) in year y.

Commodity Balances

For a given crop, the national commodity balance consists of four elements: i) the quantity produced from the study area; ii) the quantity produced from outside the study area; iii) the net export or net import; and iv) the national demand or consumption of the commodity.

With the exception of wheat and date palm crops, commodity balance constraint requires that the sum of the supply from the study area plus net imports are greater than or equal to the excess demand (total demand less production from outside the study area). Date palm and wheat are export crops. The commodity balance for date palm shows that production from the study area must be greater than or equal to the excess demand plus net exports of dates. The commodity balance for wheat shows that production from the study area must be greater than or equal to export demand less than the excess supply from outside the study area. Respectively, these different commodity balances are illustrated in algebraic forms as follows:

$$ED^{y}_{jn} - NI^{y}_{jn} - GS^{y}_{jh} \leq 0$$

$$ED^{y}_{dn} + NE^{y}_{dn} - GS^{y}_{dh} \leq 0$$

$$NE^{y}_{wn} - ES^{y}_{wn} - GS^{y}_{wh} \leq 0$$

where,

ED^{y}_{jn} = excess national demand for j^{th} crop in year y.

NI^{y}_{jn} = net national import for j^{th} crop in year y.

GS^y_{jh} = average production from the study area for j^{th} crop in year y.

ED^y_{dn} = excess national demand of date palm in year y.

NE^y_{dn} = net national export of date palm in year y.

GS^y_{dh} = average production of date palm from the study area in year y.

ES^y_{wn} = excess national supply of wheat in year y.

GS^y_{wh} = average production of wheat from the study area in year y.

NE^y_{wn} = net national export of wheat in year y.

Trade Balances

The trade balances ensure that the model allows net import or net export for a given crop to certain limits. The trade balance for j^{th} crop is illustrated as follows:

$$NI^y_{jn} \leq I^y_{jn}$$

$$NE^y_{jn} \leq E^y_{jn}$$

where,

NI^y_{jn} = net national import in year y.

NE^y_{jn} = net national export in year y.

I^y_{jn} = net import limit in year y.

E^y_{jn} = net export limit in year y.

Non-negativity Constraints

Non-negativity constraints ensure positivity for all activities in the model.

$$X^y_{jn},\ ED^y_{jn},\ ES^y_{jn},\ NI^y_{jn},\ NE^y_{jn} \geq 0$$

Data Components of the Model

Data for the model were obtained from several sources. The prominent data sources are: i)publications of Ministry of Agricultural and Water, ii)publications of Ministry of Finance and National Economy (MOFANE), iii)publications of Food and Agriculture Organization (FAO), and 4)Ph.D. dissertations.

The lack of available data is always a problem for sector models. The current model required data concerning the interconnected regional aquifers as well as the usual input-output coefficients required for normal agricultural sector models.

Average annual data from 1985 to 1990 have been used to represent the base year LP model. The 1990 data are the latest published data about crop production and cultivated land in Saudi Arabia.

Commodity Balances

i. Domestic Commodity Production

The data on domestic commodity production were obtained from the agricultural statistical year book (ASYB) and the agricultural census by regional agricultural departments (ACRDA). The ASYB provides estimates of crop production at national and regional levels by traditional farms and by specialized farms. Specialized farms tend to concentrate on producing one main crop such as wheat, vegetables, or fodders. Traditional farms produce a variety of crops.

Unfortunately, the most recent publications of the ASYB are limited to crop production and crop area at national and regional levels. The ACRDA presents data on the crop by regions and at the national level. For example, the ACRDA presents information for the Eastern Province which includes Al-Hassa and Dammam Areas. The ACRDA did provide crop production estimates for the study area for year 1982. The information provided in ACRDA and ASYB were adjusted to calculate the study area's crop production between 1985 to 1990 as follows:

$$PR_{jhr} = \frac{TP_{jh}}{TP_{jr}}$$

$$TP^{y}_{jh} = PR_{jhr} * TP^{y}_{jr}$$

where,

PR_{jhr} = ratio of j^{th} crop production in the study area (h) to the total crop production in the region (r) in year 1982 measured in tons.

TP_{jh} = total crop production of j^{th} crop in the study area (h) in year 1982 measured in tons.

TP_{jr} = total crop production of j^{th} crop in the region (r) in year 1982 measured in tons.

TP^{y}_{jh} = total crop production of j^{th} crop in the study area (h) in year (y) measured in tons.

TP^{y}_{jr} = total crop production of j^{th} crop in the region (r) in year (y) measured in tons.

y = 1985, 1986,..., 1990.

The ratio of crop production in the study area to total regional crop production is shown in *Table X*. Average crop production in the study area as a percentage of total regional

TABLE X

RATIO OF CROP PRODUCTION IN THE STUDY AREA TO TOTAL CROP PRODUCTION IN EASTERN SAUDI ARABIA, 1982.

Crop	Production in Eastern Region (ton)	Production in Al-Hassa Area (ton)	Ratio
a. Winter Crops			
Wheat	27460	22760	0.82
Tomato	7957	4560	0.57
Eggplant	1727	762	0.44
Squash	1152	719	0.62
Cucumber	986	372	0.38
Dry Onion	1519	1241	0.82
Carrot	2301	2138	0.93
b. Summer Crops			
Tomato	6974	2773	0.40
Eggplant	2357	806	0.34
Squash	2191	893	0.41
Watermelon	3460	1865	0.54
Potato	315	219	0.70
Okra	704	314	0.45
Cucumber	842	445	0.53
c. Perennial Crops			
Date Palm	86055	67378	0.78

Source: MOAW, The Agricultural Census by Regional Department of Agricultural (ACRDA). Saudi Arabia, 1982.

production, average national crop production, and average crop production outside the study area between 1985 to 1990 are provided in *Table XI*. Average crop yield in the study area, which is equivalent to regional average yield, is shown in *Table XII*.

Crop Production Activities: Production activities from the study area (X_{jh}) were developed for 13 major crops grown in Eastern Saudi Arabia. They were wheat(WH), tomatoes (TM), potatoes (PO), dry onions (ON), watermelon (WM), okra (OK), cucumbers (CU), eggplants (EP), date palm (DP), carrots (CR), alfalfa (AL), squash (SQ), and sorghum (SR). Some crops are grown in the winter season, some in the summer season, and some are grown throughout the year. Winter crops are generally planted in November-December and harvested in March. Summer crops are generally planted in March- May and harvested in August-September (ACRDA, 1982).

The CROPWAT model developed by *Smith (1992)* was used to estimate the yield response of each crop produced in the study area to different numbers and/or timing of irrigation applications. CROPWAT is a computer program that calculates crop water requirements and irrigation requirements from climatic and crop data. This program allows the development of irrigation schedules for different management conditions and the expected yield for each irrigation schedule. The use of CROPWAT model enables the LP model to contain more than one

TABLE XI

AVERAGE CROP PRODUCTION IN THE STUDY AREA AS A PERCENTAGE OF AVERAGE CROP PRODUCTION IN EASTERN SAUDI ARABIA, 1985 TO 1990.

(SPECIALIZED AND TRADITIONAL FARMS)

(TONS)

Crop	Production in Saudi Arabia	Production in the Rest of Nation	Production in Eastern Region	Production in Al-Hassa Area
a. Winter Crops				
Wheat	2895644	2839182	68509	56462
Tomato	198582	187782	18844	10800
Potato	15971	13887	2997	2084
Eggplant	29954	28373	3582	1580
Squash	15816	14865	1523	951
Cucumber	38165	36837	3524	1328
Dry Onion	13878	12862	1243	1015
Carrot	18813	17489	1425	1324
b. Summer Crops				
Tomato	179591	174799	12051	4792
Eggplant	25763	25049	2089	714
Squash	37312	36150	2851	1162
Watermelon	394542	392259	4235	2283
Potato	21776	20000	2556	1777
Okra	13394	12865	1187	529
Cucumber	43749	41257	4714	2492
c. Perennial Crops				
Date Palm	496554	452030	56866	44524
Alfalfa	619163	614218	22871	4945

Source: MOAW, Agricultural Statistical Year Book (ASYB), 1990-1992. Saudi Arabia, 1990-1994.

TABLE XII

AVERAGE QUANTITY OF CROP PRODUCTION, CROP AREA, AND CROP YIELD IN THE STUDY AREA, 1985-1990.

(SPECIALIZED AND TRADITIONAL FARMS)

Crop	Production (ton)	Irrigated Area (ha)	Crop Yield (ton/ha)
a. Winter Crops			
Wheat	56462	13728	4
Tomato	10800	274	39
Potato	2084	107	19
Eggplant	1580	66	24
Squash	951	44	22
Cucumber	1328	53	46
Dry Onion	1015	103	10
Carrot	1324	80	7
b. Summer Crops			
Tomato	4792	105	46
Eggplant	714	33	22
Squash	1162	67	17
Watermelon	2283	161	14
Potato	1777	99	18
Okra	529	69	8
Cucumber	2492	29	47
Sorghum	---	---	12
c. Perennial Crops			
Date Palm	44524	7636	6
Alfalfa	4945	155	10

Source: MOAW, Agricultural Statistical Year Book (ASYB), 1990-1992. Saudi Arabia, 1990-1994.
Sorghum crop yield is taken from Humaidan, 1980.

activity for each crop showing the yield response to different irrigation timings and applications. Having more than one activity for each crop was to determine crop mixes that give the optimal use of water in the study area. The estimated yield response of selected crops to different irrigation applications and/or timings are presented in *Table XIII*.

The corresponding value in the objective function of the LP model for each X_{jh} activity represents the average variable cost per hectare. It is the sum of production costs, the farm to wholesale marketing margin, and the pumping costs. *Production costs* consist of four main elements: i)fertilizer cost; ii)chemical cost; iii)machinery cost; and iv)other cost. The other cost includes inputs such as crop seeds. The break-down of the production costs for the crops in the study area is shown in *Table XIV*. Labor requirements are entered as coefficients in the tableau and a separate labor hiring activity is used to account for labor costs.

The margin is the difference between the wholesale price and the farm gate price:

$$M_j = WSP_j - FGP_j$$

where,

M_j = margin for producing a hectare of j^{th} crop.

WSP_j = wholesale price for j^{th} crop (SR/ton), which is the difference between retail price (RP_j) and marking margin (Mm_j).

FGP_j = farm gate price for j^{th} crop (SR/ton), which accounts for production cost, pumping cost, land rent, and

TABLE XIII

SELECTED RESULTS OF THE CROPWAT PROGRAM

	Full Irrigation		Medium Irrigation		Low Irrigation	
Crop	Irrigation Requirement (cu m/ha)	Yield (ton/ha)	Irrigation Requirement (cu m/ha)	Yield (ton/ha)	Irrigation Requirement (cu m/ha)	Yield (ton/ha)
Wheat	4736	4.11	3969	3.92	3684	2.99
Tomato	9913	45.72	6340	42.11	5013	36.94
Dry Onion	3687	9.86	3645	9.62	3642	9.61
Potato	4252	19.43	3913	17.18	3803	16.92
Watermelon	11215	14.18	10750	13.30	9040	11.88
Date Palm	14887	5.83	10476	4.73	6985	3.71
Alfalfa	27286	10.26	24177	9.18	22116	8.15
Sorghum	11783	12.20	10827	10.78	6594	8.30
Cucumber	8835	47.39	8752	42.80	7821	42.46
Eggplant	14218	21.68	11187	19.12	10952	17.45
Okra	8975	7.69	8338	7.52	8304	7.03
Carrot	6649	16.16	6387	15.45	5720	14.37

TABLE XIV

ELEMENTS OF PRODUCTION COSTS.

(SR/HA)

Crop	Fertilizer Cost	Chemical Cost	Machinery Cost	Other[1] Cost	Total Cost
Wheat	310	0	1952	480	2742
Tomato	2915	1840	1924	1000	7679
Potato	605	720	1436	6750	9511
Dry Onion	2980	720	1666	385	5751
Water Melon	3097	720	874	175	4866
Date Palm	1320	0	375	0	1695
Alfalfa	803	143	3253	1103	5302
Sorghum	358	120	1117	105	1700
Cucumber	411	720	874	245	2250
Eggplant	4015	720	874	1000	6609
Okra	4600	1040	1374	476	7490
Carrot	897	240	986	216	2339
Squash	2980	720	874	225	4799

Source: Humaidan, 1980.

1) Other cost = the cost of purchasing other inputs (seeds).

labor cost.

Table XV shows the retail price, wholesale price, marketing margin, farm gate price, and margin.

Pumping costs were calculated on a basis of different levels of: i)static water and the associated pumping drawdown, and ii)pumping efficiency. The pumping drawdown varies in accordance to the type of aquifer as to whether it is confined or unconfined. *A confined aquifer* is an aquifer whose top and bottom are bounded by confining beds, and groundwater is under pressure higher than the atmospheric pressure (Driscoll, 1986). *An unconfined aquifer* is an aquifer whose bottom is bounded by a confining bed, and groundwater is under no pressure but the atmospheric (Barefoot and Schwab, 1990). The confined aquifer becomes an unconfined aquifer when the water table drops below the top of the confining bed.

Pumping Cost

The cost of pumping irrigation water is estimated by using the following formula as given by *Elliott (1995)*:

$$PC = C * \frac{Q}{E_e\ E_p} * TDH * C_e$$

where,

PC = annual pumping cost, measured in Riyals per year.

C = the energy required with 100 percent efficiency to pump one cubic meter against a meter of head.

Q = total annual pumped water, measured in cubic meters.

TDH = total dynamic head, measured in meters.

TABLE XV

AVERAGE PRICES AND MARKETING MARGINS, 1985-1990

(SR/TON)

Crops	Retail Price	Marketing Margin	Wholesale Price	Farm Gate Price	Margin
a. Winter Crops					
Wheat	3847	979	2000	1141	859
Tomato	4277	3387	890	379	511
Potato	3322	2375	946	684	262
Eggplant	4075	2589	1486	538	948
Squash	4928	3524	1404	457	947
cucumber	4660	3332	1327	152	1176
Dry Onion	2732	1663	1069	1044	25
Carrot	4240	3495	745	435	310
b. Summer Crops					
Tomato	4277	3387	890	327	563
Potato	3322	2375	946	743	203
Eggplant	4075	2589	1486	600	886
Squash	4928	3524	1404	574	830
Water Melon	2562	1283	1279	636	643
Okra	9983	6343	3640	1530	2109
Cucumber	4660	3332	1327	151	1177
Sorghum	2877	918	1958	415	1544
c. Perennial Crops					
Date Palm	7432	6247	3000	1711	1289
Alfalfa	1500	479	1021	998	23

Sources: 1)MOFANE, Statistical Year Book. Saudi Arabia, 1985-90; Kahatani, 1989.
2)Marketing margins were calculated as a percentage of the crop's retail price based on estimates from Duwais, 1990; Kahatani, 1989; and USDA, 1987.
3)Wholesale price of wheat and date palm are taken from Duwais, 1990.

C_e = energy cost, measured in Riyals per a unit of energy.

E_e = engine efficiency, fraction.

E_p = pump efficiency, fraction

The two critical variables in the formula are the total dynamic head and the overall pumping plant efficiency. The efficiency of a particular pump depends on the pump impellers. As the water declines the efficiency of the pump will change and the rate of output from the pump will decline if the impeller speed remains constant. The piezometric head of the aquifer is expected to decline during the season as the length of the pumping period increases and from one year to the next.

The problem of establishing a feasible pumping efficiency for the conditions in the study area was solved in two steps. *The first step* was to use available computer programs to estimate the pumping drawdown in response to the length of pumping season and the rate of discharge from the aquifer. The results from the computer programs are used to empirically relate the pumping drawdown to the number of days of pumping and the rate of discharge by using multiple regression. *The second step* was to use the regression equations from the first step in the second computer program in which the empirically estimated head characteristic curves could be used to evaluate alternative irrigation pumps for various conditions of the aquifer, which include: i)depth of pumping; ii)rate of discharge; and iii)state of aquifer (confined, unconfined, or undergoing transition from a confined to unconfined).

Estimating of Pumping Drawdown

Pumping test models developed by *Dawson and Istok (1991)* were used to estimate pumping drawdown in three aquifer conditions in response to the rate of aquifer withdrawals and the length of pumping season. The three aquifer conditions expected to be encountered were: i) a partial penetration into a confined aquifer; ii) a partial penetration into an unconfined aquifer; and iii) conversion from confined to unconfined aquifer.

Pumping drawdown was estimated for partially penetrating wells where the pumps were set at 100, 200, 300, 400, and 500 meters penetration into the aquifer. Each level represents the distance from aquifer top to the bottom of the well screen. The last level of pump setting represented full penetrating of Umm-Er-Radhuma aquifer in the study area. At each level of pump setting, pumping drawdown was estimated at various levels of pumping time, and well density.

The governing equations and the initial conditions for each aquifer condition as given by *Dawson and Istok (1991)* are summarized in sequence as follow:

Partial Penetration Confined Model (PPC)

The governing equation of the PPC mathematical model is the combination of Darcy's Law with the principle of conservation of mass in a radial coordinate system,

$$\left(\frac{K_r}{K_z}\right)^2 \left[\frac{\partial^2 s}{\partial r^2} + \left(\frac{1}{r}\right)\frac{\partial s}{\partial r}\right] + \frac{\partial^2 s}{\partial z^2} = \left(\frac{S}{K_z m}\right)\frac{\partial s}{\partial t}$$

where,

K_r = aquifer horizontal hydraulic conductivity.

K_z = aquifer vertical hydraulic conductivity.

S = aquifer storage coefficient.

s = well drawdown.

r = radial distance from the pumping well.

z = vertical distance from the top of aquifer.

t = time.

The initial condition of the PPC model stated that drawdown is zero everywhere before pumping starts,

$$s(r, z, t) = 0$$

The boundary conditions of the PPC model are as follows: i)drawdown is zero at an infinite distance from the pumping well,

$$s(r = \infty, z, t) = 0$$

ii)there is no vertical flow at the top and bottom of the aquifer,

$$\frac{\partial s(r, z=m, t)}{\partial z} = 0$$

$$\frac{\partial s(r, z=0, t)}{\partial z} = 0$$

iii)flow of groundwater to the pumping well is constant and uniform over the screened interval,

$$\lim_{r \to 0}\left[(l-d)r\frac{\partial s}{\partial r}\right] = 0 \qquad 0 < z < d$$

$$\lim_{r \to 0}\left[(l-d)r\frac{\partial s}{\partial r}\right] = -\frac{Q}{2\pi K_r} \qquad d < z < l$$

$$\lim_{r \to 0}\left[(l-d)r\frac{\partial s}{\partial r}\right] = 0 \qquad l < z < m$$

where,

l = distance from top of the aquifer to bottom of pumping well screen.

d = distance from top of the aquifer to top of pumping well screen.

Conversion from Confined to Unconfined Model (CCUC)

There are two governing equations to execute the CCUC model. Both are derived through combining Darcy's Law with the principle of conservation of mass in a radial coordinate system. The governing equation for the unconfined zone is,

$$\frac{\partial^2 h_1}{\partial r^2} + \frac{1}{r}\frac{\partial h_1}{\partial r} = \frac{S_1}{Km}\frac{\partial h_1}{\partial t} \qquad 0 \le r \le R$$

The governing equation for the confined zone is,

$$\frac{\partial^2 h_2}{\partial r^2} + \frac{1}{r}\frac{\partial h_2}{\partial r} = \frac{S_2}{Km}\frac{\partial h_2}{\partial t} \qquad r \ge R$$

The initial condition for the CCUC model stated that before the start of pumping, drawdown is zero and the head at each point along with the initial piezometric head H are equal,

$$h_2(r,t = 0) = H \qquad 0 \le r \le \infty$$

The boundary conditions of the CCUC model are as follows: i) at the radius of water table conversion, the head and the thickness of the aquifer are equal and the head has a continuous derivative,

$$h_2(r = R,\ t) = h_1(r = R,\ t) = m \qquad t \succ 0$$

$$\frac{\partial h_1(r=R,t)}{\partial r} = \frac{\partial h_2(r=R,t)}{\partial r} \qquad t \succ 0$$

ii) flow of groundwater to the pumping well is constant and uniform over the screened interval,

$$\lim_{r\to 0} 2\pi r T \frac{\partial h_1(r=0,t)}{\partial r} = Q \qquad t > 0$$

iii)at an infinite distance from the pumping well, drawdown is zero and the head along with the initial piezometric head H are equal,

$$h_2(r = \infty,\ t) = H \qquad t \geq 0$$

where,

R = radial distance from the pumping well to the edge of the confined zone.

H = initial piezometric head.

Partial Penetration Unconfined Model (PPUC)

The governing equation for the PPUC mathematical model along with its initial condition and boundary conditions are assumed to be equivalent to that of PPC model except changing the storage coefficient (S) stated in the governing equation of the PPC model to specific storage (S_s) in the PPUC model as follows:

$$\left(\frac{K_r}{K_z}\right)^2 \left[\frac{\partial^2 s}{\partial r^2} + \left(\frac{1}{r}\right)\frac{\partial s}{\partial r}\right] + \frac{\partial^2 s}{\partial z^2} = \left(\frac{S_s}{K_z m}\right)\frac{\partial s}{\partial t}$$

ii. Domestic Demand

The average quantity demand at the national level for the j^{th} commodity was calculated as follows:

$$TD_{jn} = TP_{jn} + I_{jn} - E_{jn}$$

where,

TD_{jn} = average domestic demand for the j^{th} crop, measured in tons.

TP_{jn} = average national production for the j^{th} crop, measured in tons.

I_{jn} = average national imports for the j^{th} crop, measured in tons.

E_{jn} = average national exports for the j^{th} crop, measured in tons.

The average national demand, import, and export for the given crops are presented in *Table XVI*. Extensive use of linearized demand and supply functions was implemented. To linearize the demand and the supply functions for a given commodity, a set of demand or supply curves was developed. Linearizing the demand and the supply functions required the following information: i)the initial crop price; ii)the initial quantity demanded at the national level; iii)the initial quantity produced from the rest of nation; and iv)demand and supply elasticities.

The demand and supply functions were subdivided into 6 segments. Each segment represented the quantity demand or supplied at a specified price. The price of the first segment represented the sum of production costs; margin; and pumping cost. The price of the last segment was set at a level equivalent to the equilibrium price where quantity demanded at the national level was equal to the production from the rest of the nation.

In mathematical notation, the equilibrium price for j^{th} crop was derived by equating the demand function (equation 15) with the supply function (equation 17) and solving for price as shown below,

TABLE XVI

AVERAGE DOMESTIC CONSUMPTION, IMPORTS, AND EXPORTS IN SAUDI ARABIA

(TONS)

Crop	Domestic Consumption	National Import[1]	National Export[1]
Wheat	1014500	131308	1567918
Tomato	508843	132560	1890
Potato	141995	106123	1875
Eggplant	59949	4233	---
Squash	61104	7977	---
Cucumber	94430	12516	---
Dry Onion	138188	125965	1655
Carrot	18813	---	---
Sorghum	27782	---	---
Watermelon	398984	17145	12703
Okra	15124	1730	---
Date Palm	473309	6208	29453
Alfalfa	619163	---	---

Sources: 1)MOAW. Agricultural production and it's Impact on Foreign Trade. Saudi Arabia, 1994.

Domestic consumption was calculated but data on wheat was obtained from MOAW. Agricultural Statistics Year Book, 1992. Saudi Arabia, 1993.

$$EP_j = \frac{\left(\frac{d_j}{dd_j} - \frac{c_j}{cc_j}\right)}{\left(\frac{1}{dd_j} - \frac{1}{cc_j}\right)}$$

Table XVII presents the initial crop price, the initial quantity demanded at the national level, the initial quantity produced from the rest of the nation, demand elasticity, supply elasticity, and the equilibrium price.

iii. Domestic and International Prices

Table XVIII illustrates the domestic wholesale price, C.I.F. import price, and F.O.B. export price. The trade section of the PLP model contains national imports or national exports. The wholesale prices for the j^{th} crops were higher than the international C.I.F. import price because of the transportation cost. For the same reason, the local wholesale price for the export crops is lower than the international export price (F.B.O). To simplify the model, the C.I.F. and F.O.B. prices were adjusted to the domestic whole sale prices.

iv. Selling Activities

The set of excess demand activities (ED_{ji}) for each commodity calculates the additional consumer's surplus that can be obtained from production of the j^{th} crop from the study area. Each activity within the set (ED_{ji}) is associated with a price P_{ji} and an upper bound Q_{ji}. Assume the subscripts are such that $P_{j1} > P_{j2} > \ldots > P_{jn}$. The corresponding upper bound Q_{j1} is the amount that can be sold from the study area at the

TABLE XVII

AVERAGE DOMESTIC DEMAND, PRODUCTION, CROP PRICE, AND ELASTICITIES OF DEMAND AND SUPPLY

Crops	Demand Elasticity	Price SR/ton	Domestic Demand (ton)	Inverse demand Function Intercept	Inverse Demand Function Slope	Production from Rest of Nation (ton)	Inverse Supply Function Intercept	Inverse Supply Function Slope	Supply Elasticity	Equilibrium Price[1] (Sr/ton)
Winter Crop										
Wheat	-0.14791	2000	1014500	-0.0133284	15522	2839182.00	6162	-17494749575	0.0000001	2000
Tomato	-0.51069	890	267198	-0.0065212	2632	187782	9557	-1794571019	0.0000005	1408
Potato	-0.46371	946	60078	-0.0339672	2987	13887	1852	-25713538	0.0000368	2515
Eggplant	-0.34246	1486	32229	-0.1345952	5823	28373	28	-798330	0.0018574	2002
Squash	-0.41000	1404	18191	-0.1882267	4828	14865	51	-754412	0.0018574	2027
Cucumber	-0.42879	1327	43997	-0.0703657	4423	36837	32	-1163996	0.0011391	1830
Dry Onion	-0.81054	1069	138188	-0.0095431	2388	12862	84	-1076330	0.0009921	2265
Carrot	-0.03534	745	18813	-1.1203997	21823	17489	46	-796596	0.0009342	2192
Summer Crop										
Tomato	-0.51069	890	241645	-0.0072108	2632	174799	10266	-1794571019	0.0000005	1372
Potato	-0.46371	946	81916	-0.0249119	2987	20000	1286	-25713538	0.0000368	2489
Eggplant	-0.34246	1486	27720	-0.1564858	5823	25049	32	-798330	0.0018574	1902
Squash	-0.41000	1404	42914	-0.0797867	4828	36150	21	-754412	0.0018574	1941
Watermelon	-0.25919	1279	398984	-0.0123671	6213	392259	1587	-622552298	0.0000021	1362
Okra	-1.13106	3640	15124	-0.2127727	6857	12865	35	-448971	0.0080414	4117
Cucumber	-0.57158	1327	50433	-0.0460498	3650	41257	28	-1163996	0.0011391	1749
Sorghum	-0.24242	1958	27782	-0.2907694	10036	27782	616588	-17129735268	0.0000001	1958
Perennial Crop										
Date Palm	-0.14431	3000	473309	-0.0439218	23789	452030	5786	-2615515745	0.0000011	3935
Alfalfa	-0.33598	1021	619163	-0.0049086	4060	614218	14542	-8932075169	0.0000001	1045

Sources: Demand elasticities for wheat, tomato, potato, onion, carrot, okra, water melon, eggplant, sorghum, alfalfa (beef), and date palm are taken from Kahatani, 1989; squash is taken from Duwais, 1990. average winter vegetable demand elasticities are used as proxy for winter cucumber; average summer vegetable demand elasticities are used as proxy for summer cucumber.
Supply elasticities are calculated in the study as a percentage change in quantity supplied by producers outside the study area associated with one percentage change in price.

TABLE XVIII

AVERAGE DOMESTIC WHOLESALE, C.I.F. IMPORT, AND F.O.B. EXPORT PRICES IN SAUDI ARABIA

(SR/TON)

Crop	Average Price		
	Wholesale	Import[1] C.I.F.	Export[1] F.O.B.
Wheat	2000	1312	445
Tomatoes	890	684	1320
Potatoes	946	747	1013
Dry Onion	1069	642	1032
Egg plant	1486	701	---
Okra	3640	1908	---
Water Melon	1279	1219	1170
Date Palm	3000	1972	2182
Cucumber	1327	680	---
Squash	1404	678	---

Sources: 1)MOAW. Agricultural Production and Its Impact on Foreign Trade. Saudi Arabia, 1994.

national price P_{j1}. After ED_{j1} reaches the upper bound, if any additional quantity is sold from the study area, it must be sold at the next lower price P_{j2}. This continues until the price of the last unit sold is equal to the marginal cost of producing the last unit. The consumer surplus generated from j^{th} commodity is $\sum_i ED_{ji}P_{ji}$. A similar process applies in the case of excess supply activities for export crops.

Resource Use

Input-output coefficients are measured on a basis of the amount of each resource required to produce one hectare of each activity.

i. Cultivated Land

The data on cultivated crop land at national and regional levels were obtained from the agricultural statistical yearbook (ASYB). Utilizing the information provided in *Tables XI and XII*, crop land for j^{th} crop in the study area is calculated as follows:

$$TL_{jhn} = \frac{TP_{jhn}}{Y_{jhn}}$$

where,

TL_{jhn} = average annual crop area in the study area, measured in hectares (ha).

Y_{jhn} = average annual crop yield in the study area, measured in ton/ha.

TP_{jhn} is as defined earlier.

Table XIX shows the allocation of cultivated land among the different farming crops nation-wide, in the Eastern

TABLE XIX

AREA PLANTED TO MAJOR CROPS BY SEASON IN SAUDI ARABIA AND THE STUDY AREA

(HECTARES)

Crop	Irrigated Land Area			
	Saudi Arabia	Rest of the Nation	Eastern Saudi Arabia	Al-Hassa Area
a. Winter Crops				
Wheat	672155	658427	16657	13728
Tomato	10988	10713	476	274
Potato	832	725	154	107
Eggplant	2850	2784	149	66
Squash	11331	11288	70	44
Cucumber	1772	1719	100	53
Dry Onion	1432	1329	126	103
Carrot	1238	1158	86	80
b. Summer Crops				
Tomato	12694	12290	264	105
Eggplant	2182	2149	96	33
Squash	3023	2956	165	67
Watermelon	19398	19237	299	161
Potato	1165	1066	142	99
Okra	2125	2056	154	69
Cucumber	1648	1619	76	29
c. Perennial Crops				
Date Palm	65318	57681	9753	7636
Alfalfa	49463	49308	2229	155

Source:MOAW, Agricultural Statistical Year Book (ASYB). Saudi Arabia, 1990-1993.

Average crop area in outside the study area = average national crop area - average crop area in the study area.

Province, in the study area, and outside the study area.

ii. Labor Force

The data on the total agricultural labor force in Saudi Arabia and in the study area were obtained from ACRDA, 1982. The ACRDA presented the agricultural labor statistics on a basis of:i)family worker labor (unpaid) or hired labor (paid); and ii)by growing season (winter or summer). *Table XX* shows the total agricultural labor in Saudi Arabia, in the study area, and the ratio between the two totals.

Humaidan (1980) developed enterprise budgets for crop production in Al-Hassa area with a surface irrigation system. The labor requirements to produce one hectare of a given crop are almost identical except for irrigation. *Heemst et al., (1981)* stated that irrigation labor requirements differ from one irrigation system to another. The average hours of labor required to irrigate a single hectare using surface, sprinkler, and trickle systems are proportionally: 1 : 0.59 : 0.17 percent. In other words, if irrigating one hectare of a given crop required 100 hours of labor using a surface system, the same hectare would require 59 hours using a sprinkler system, and 17 hours using a trickle system.

The information provided by *Humaidan and Heemst et al.*, was used to develop labor requirements and labor costs for each crop using the different irrigation systems. The labor requirements for surface, sprinkler, and trickle irrigation

TABLE XX

TOTAL AGRICULTURAL LABOR FORCE IN SAUDI ARABIA AND IN THE STUDY AREA, 1982.

(WORKERS)

Labor Discrepancy	Saudi Arabia	Al-Hassa Area	Ratio
Family Labor	303924	10195	0.03
Hired Labor	94932	31295	0.33
Total Labor	398856	41490	0.10

Source: MOAW, the agricultural census by regional departments of agricultural (ACRDA). Saudi Arabia, 1982.

systems are presented in *Table XXI* shows.

iii. Water Requirements

Crop water requirements (CWR_j) are the prominent input-output coefficients in this study. The total water requirement is defined as the volume of water required to meet a crop's net water requirement, leaching requirement, and water losses (AL-Zeid at al. 1988). Rainfall is not a reliable source for crop farming in the study area because of its erratic and negligible quantity.

To approximate the optimal total water requirement for a given crop, the net water requirement was adjusted according to the efficiency of the irrigation system. Irrigation efficiency was defined as the amount of water retained in the root zone as a percentage of the total water conveyed from the source to the plant. The irrigation efficiencies assumed for the climate of the study area were: 55 percent for the surface system; 70 percent for the sprinkler system; and 85 percent for the trickle system (Al-Zeid et al., 1988).

Net monthly crop water requirements were adopted from *Al-Zeid et al. (1988) and Humaidan (1980). Al-Zeid et al. (1988)* stated that the monthly crop water requirements assume: disease-free crops, that crops are grown in large areas, and that crops have enough water and fertilizers.

The root zone could be leached of salt by a heavy irrigation performed before the growing season, during and/or

TABLE XXI

LABOR REQUIREMENTS BY IRRIGATION SYSTEM.

(HOUR/HECTARE)

Crop	Surface System	Sprinkler System	Trickle System
Wheat	136	109	82
Tomato	875	773	668
Potato	397	360	322
Eggplant	730	642	552
Squash	590	537	482
Cucumber	540	468	395
Dry Onion	482	421	358
Carrot	545	473	400
Watermelon	425	355	284
Okra	450	397	342
Sorghum	311	264	216
Date Palm	1004	654	576
Alfalfa	474	358	240

after the growing season, depending on the availability of water. A leaching requirement was calculated by assuming the study area had: i) a well-drained sandy and sandy loam soil; ii)there was no rainfall; and iii) the leaching efficiency was 90 percent (Al-Zeid et al. 1988). The total water requirements for crop and leaching of salt were calculated as,

$$TIR_{js} = \frac{ET_j}{EI_s} * \frac{1}{1 - LR_{js}}$$

where,

TIR_{js} = total water requirement for j^{th} crop.

Et_{jt} = monthly crop water requirement for j^{th} crop.

EI_s = irrigation efficiency for system s.

LR_{js} = leaching requirement for j^{th} crop with system s.

The leaching requirements for the different irrigation systems are shown in *Table XXII*. Monthly water requirements for each irrigation system are shown in *Tables XXIII, XXIV, and XXV*. The total water requirements are measured in terms of cubic meters/hectare.

The Projected PLP Model

The LP model was used to maximize the one-year net social benefits in the study area that could be obtained with each possible irrigation system configuration when pumping from each selected depth of the static water table. Parametric linear programming solutions were obtained with projected population and demand conditions expected for the years 1990,

TABLE XXII

LEACHING REQUIREMENTS AS A FRACTION OF TOTAL IRRIGATION REQUIREMENTS BY IRRIGATION SYSTEM

Crop	Surface System	Sprinkler System	Trickle System
Wheat[a]	0.05	0.04	0.04
Tomato	0.13	0.07	0.07
Potato	0.20	0.09	0.09
Eggplant[b]	0.18	0.08	0.08
Squash[b]	0.18	0.08	0.08
Cucumber	0.13	0.09	0.09
Dry Onion	0.29	0.11	0.11
Carrot[b]	0.18	0.08	0.08
Watermelon	0.13	0.05	0.05
Okra[b]	0.18	0.08	0.08
Sorghum[a]	0.08	0.05	0.05
Date Palm	0.05	0.03	0.03
Alfalfa[a]	0.14	0.05	0.05

Source: Al-Zeid et al., "Guide for Crop Irrigation Requirements...", 1988.

a.Leaching requirements for wheat, sorghum, and alfalfa using trickle irrigation system are estimates.
b.Average leaching requirements for vegetables were used for eggplant, okra, carrot, and squash

TABLE XXIII

TOTAL MONTHLY WATER REQUIREMENTS FOR THE SURFACE IRRIGATION SYSTEM, FULL IRRIGATION.[a]

(CUBIC METERS/HECTARE)

Crop	Date of Planting[b]	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
a. Winter Crops													
Wheat	1015	2335	1263								1060	2071	2335
Wheat	1101	2136	1554									1493	2136
Tomato	0801								2966	4570	4898	3461	2027
Potato	1001	1925									1823	3120	2795
Eggplant	0701							4377	6019	7149	5198	2780	
Squash	1001										2586	2587	1500
Cucumber	0901									2821	2776	2740	1421
Dry Onion	0901	2619	3442	2940						3526	4051	2940	2700
Dry Onion	1101	2822	886									2994	2740
Carrot	0821								1359	4832	4309	3045	1125
b. Summer Crops													
Tomato	0101	1005	2332	5131	6169	6080							
Potato	0101	2043	2884	4443	4555								
Eggplant	0301			2121	4505	8372	9930	6445					
Squash	0101	1129	2016	3641									
Water Melon	0301			2138	3511	6285	7836	3667					
Okra	0601						4964	7384	7455				
Cucumber	0301			2138	3511	6285	6531						
Sorghum	0401				2728	6066	8123	6372					
c. Perennial Crops													
Date Palm	1103	1068	1340	1899	2009	3501	3330	3857	3975	3043	1720	1148	1602
Alfalfa	1103	2556	2901	4325	4883	6816	7357	8061	6685	4820	4063	2663	2556

a)Total monthly water requirements are calculated with 55 percent irrigation efficiency.

b)The first two digits of date of Planting represent the month, while the other two digits represent day; for example wheat date of planting is 1015 means October 15.

TABLE XXIV

TOTAL MONTHLY WATER REQUIREMENTS FOR THE SPRINKLER IRRIGATION SYSTEM, FULL IRRIGATION.[a]

(CUBIC METERS/HECTARE)

Crop	Date of Planting [b]	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
a. Winter Crops													
Wheat	1015	1815	982								824	1610	1815
Wheat	1101	1661	1208									1161	1661
Tomato	0801								2180	3359	3600	2544	1490
Potato	1001	1330									1259	2155	1931
Eggplant	0701							3087	4245	5042	3666	1960	
Squash	1001										1824	1825	1058
Cucumber	0901									2119	2085	2058	1067
Dry Onion	0901	1642	2157	1843						2210	2539	1843	1692
Dry Onion	1101	1769	555									1876	1717
Carrot	0821								958	3408	3039	2148	793
b. Summer Crops													
Tomato	0101	738	1714	3771	4535	4469							
Potato	0101	1411	1992	3069	3146								
Eggplant	0301			1496	3177	5905	7003	4545					
Squash	0101	796	1422	2568									
Water Melon	0301			1538	2526	4522	5639	2639					
Okra	0601						3501	5208	5258				
Cucumber	0301			1606	2638	4721	4906						
Sorghum	0401				2075	4615	6181	4848					
c. Perennial Crops													
Date Palm	1103	822	1031	1461	1546	2694	2563	2968	3059	2342	1324	884	1233
Alfalfa	1103	1818	2063	3076	3473	4848	5233	5734	4755	3429	2890	1894	1818

a) Total monthly water requirements are calculated with 70 percent irrigation efficiency.
b) The first two digits of date of Planting represent the month, while the other two digits represent day; for example wheat date of planting is 1015 means October 15.

TABLE XXV

TOTAL MONTHLY WATER REQUIREMENTS FOR THE TRICKLE IRRIGATION SYSTEM, FULL IRRIGATION.[a]

(CUBIC METERS/HECTARE)

Crop	Date of Planting [b]	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
a. Winter Crops													
Wheat	1015	1495	809								679	1326	1495
Wheat	1101	1368	995									956	1368
Tomato	0801								1795	2766	2965	2095	1227
Potato	1001	1095									1037	1775	1590
Eggplant	0701							2542	3496	4152	3019	1615	
Squash	1001										1502	1503	871
Cucumber	0901									1745	1717	1695	879
Dry Onion	0901	1352	1777	1517						1820	2091	1517	1393
Dry Onion	1101	1457	457									1545	1414
Carrot	0821								789	2807	2503	1769	653
b. Summer Crops													
Tomato	0101	608	1411	3106	3734	3680							
Potato	0101	1162	1641	2527	2591								
Eggplant	0301			1232	2616	4863	5767	3743					
Squash	0101	655	1171	2114									
Water Melon	0301			1267	2081	3724	4644	2173					
Okra	0601						2883	4289	4330				
Cucumber	0301			1322	2172	3888	4040						
Sorghum	0401				1709	3801	5090	3993					
c. Perennial Crops													
Date Palm	1103	677	849	1203	1273	2218	2110	2444	2519	1928	1090	728	1015
Alfalfa	1103	1497	1699	2533	2860	3993	4310	4722	3916	2824	2380	1560	1497

a) Total monthly water requirements are calculated with 85 percent irrigation efficiency.
b) The first two digits of date of Planting represent the month, while the other two digits represent day; for example wheat date of planting is 1015 means October 15.

2005, 2020, 2035, and 2050. The national domestic demand, net imports, and net exports for each commodity were expected to increase at the rate of population growth as shown in *Table XXVI*. Production outside the study area was assumed to grow at a rate consistent with an increase in arable land, from 1.4 million hectares in 1990 to 4.6 million hectares by year 2050. The growth rate of production outside the study area was derived mathematically as,

The growth function in linear form is,

$$X_{2050} = X_{1990} \ (1 + GROW_{2050})^{T}$$

The growth function in natural log form is,

$$\ln X_{2050} = \ln X_{1990} + T \ [\ln(1+ GROW_{2050})]$$

the growth can be obtained as:

$$GROW_{2050} = \exp\left(\frac{\ln X_{2050} - \ln X_{1990}}{T}\right) - 1$$

where,

X_{2050} = expected potential arable land in year 2050 (ha).

X_{1990} = potential arable land in year 1990 (ha).

$GROW_{2050}$ = expected annual growth rate.

T = time period representing the difference between the base year (1990) and last year of study (2050).

The output of the PLP step provided a series of one-year solutions which show the maximum consumer and producer surplus for each possible state (number of irrigation wells; amount of irrigated area; and annual volume of water use) at a particular stage (year) in the planning horizon. These outputs were used as inputs in the dynamic programming model (DP).

TABLE XXVI

PREDICTED POPULATION GROWTH BY 15 YEAR INTERVALS, 1990-2050.

Year	Population (Thousand)	Population Growth (thousand)	Population Growth (percent)
1990	16271		
2005	25917	9646	59.28
2020	42085	16168	62.38
2035	65318	23233	55.20
2050	95267	29949	45.85

Source: Urban and Nightigale," World Population by Country and Region, 1950-90 and Projections to 2050.", 1993.

GROUNDWATER FLOW MODEL

The groundwater model described below was used to quantify the effect of withdrawals of water in the study area and permanent lowering of the water table. This relationship was required by the DP model to determine the impact of water use in one time period on the height of the water table in subsequent time periods and its impact on future income. Groundwater flow models were developed initially by *Trescott (1975); Trescott et al., (1976)*. These models are two-dimensional and three-dimensional finite-difference groundwater-flow models. Development of these models has made the simulation of groundwater flow possible.

McDonald and Harbaugh (1980) developed a new groundwater flow model that could be used efficiently and easily. This finite-difference model is a three-dimensional model that simulates the groundwater flow within the aquifer using a block-centered finite-difference approach. This flow model can be used to: i)simulate confined aquifers, unconfined aquifers, or a combination of both aquifers; ii)simulate flows from external sources such as areal recharge and flow to wells; iii)either two-dimensional or three-dimensional applications.

The model's equations can be solved either by using: i)the Strongly Implicit Procedure (SIP) which is a procedure that solves a large system of simultaneous linear equations iteratively; or by ii)the Slice-Successive Over Relaxation

(SSOR) which is a method that iteratively solves a system of finite-difference equations associated with the cells in the finite-difference grid.

The finite-difference model provides a series of outputs concerning the groundwater hydrology in the study area and in the region in general. This series of output provides the dynamic programming model with another series of inputs.

Groundwater Hydrology

In the study area, the Umm-Er-Radhuma is a member of a multi-aquifer system which includes: i)the Neogene aquifer; ii)the Dammam aquifer (Khobar-Alat); and iii)the Umm-Er-Radhuma aquifer. This complete groundwater system feeds the natural springs in the study area with an abundant amount of water. For this study the system was visualized and solved as a bi-layer system. The first layer consists of the Neogene and Dammam aquifers; and the Umm-Er-Radhuma represents the second layer in the system.

Hydraulic Properties of Aquifer

i. The Piezometric Head

Piezometric head is defined as the level at which water will rise in a well penetrating a confined aquifer (Driscoll, 1986). The piezometric head of the Dammam-Neogene layer is 250 meters above sea level at the western edge of the outcrop and declines in a northeast direction to 25 meters above sea level in the east near the sea coast. The average piezometric head is 150 meters above sea level at the west part of the study area and 125 meters above sea level at the eastern edge of the study area.

The piezometric head of the Umm-ER-Radhuma layer also declines along a northeast direction from 250 meters above sea level near the western outcrop to 50 meters above sea level near the sea coast. The average piezometric head in the study area is 150 meters above sea level and declines to 100 meters above sea level east of the study area. The direction of the decline in the head in both layers indicates that the general flow of groundwater is toward the northeast direction (WAOSA, 1984).

The piezometric heads in both layers are identical in the study area at 150 meters above sea level, implying the direct connection of the multi-groundwater-aquifer system near the study area. The direct connection exists at the Rus truncation window on top of the Ghawar anticline to the west of the study area.

ii. Transmissivity

Transmissivity or transmissibility is the product of the aquifer saturated thickness and hydraulic conductivity (Dawson and Istok, 1991),

$T = Km,$

where,

T = Transmissivity measured in m^2/second.

K = hydraulic conductivity measured in m/second.

m = saturated thickness measured in m.

Generally, there are variations in transmissivity values from one place to another because of the variability in aquifer thickness and hydraulic conductivity. The average tansmissivity in the Dammam aquifer was found to range between 5.7×10^{-6} to 0.9×10^{-1} m^2/s in the Khobar member and 2.6×10^{-5} to 2.9×10^{-1} m^2/s in the Alat member. The reported transmissivity values in the study area range between 5.7×10^{-6} to 5×10^{-4} m^2/s in the Khobar member; and 2×10^{-4} to 7.9×10^{-2} m^2/s in the Alat member. The average transmissivity of the Neogene aquifer is about 1.1×10^{-4} m^2/s (WAOSA, 1984); and it ranges from 7×10^{-4} to 4×10^{-2} m^2/s in the study area (Othman, 1983).

Transmissivity of Umm-Er-Radhuma was found to range between 4×10^{-5} to 1.1×10^{-2} m^2/s (Othman, 1983; WAOSA, 1984), reflecting the variability in the local and regional lithology and weathering in the aquifer (Al-Bassam, 1983).

iii. Storativity

The storativity or storage coefficient is defined as the volume of water that an aquifer or aquitard discharges from or takes into storage per unit surface area per unit change in piezometric head (Barefoot and Schwab, 1990; Dawson and Istok, 1991). The storage coefficient consists of two terms: i) specific yield (S_y) which is defined as the volume of water released from storage by gravity; and ii) specific storage (S_s) which is defined as the volume of water released from storage by water expansion and soil compression (Dawson and Istok, 1991). *Al-Bassam (1983)* stated that storativity of the confined aquifer may range between 5×10^{-5} to 5×10^{-3} , implying the requirement of a large pressure change over a large area to produce a large quantity of water.

Storativity of the Dammam aquifer was found to range between 1×10^{-4} to 2×10^{-3} (Al-Bassam, 1983). Storativity of the two productive members of the Dammam aquifer was found to be 1.32×10^{-4} to 5.34×10^{-4} in the Alat member, and 1.3×10^{-6} in the Khobar member (WAOSA, 1984). Storativity of the Neogene aquifer was found to be 2×10^{-4} in the study area (Othman, 1983). The reported storativity of the Umm-Er-Radhuma was found to range from 5×10^{-5} to 5×10^{-3} with an average of 4×10^{-4} (WAOSA, 1984).

Finite-Difference Groundwater Model

It was not possible to model the entire groundwater system in Eastern Saudi Arabia. Thus, a small regional aquifer model was developed for an area larger than Al-Hassa study area as shown in *Figure VIII*. The first upper layer for the Neogene-Dammam aquifer extends from the western boundary of the Dammam aquifer eastward to the Gulf coast. The lower layer for Umm-Er-Radhuma aquifer extends from the western boundary of Umm-Er-Radhuma eastward to the Gulf coast. The

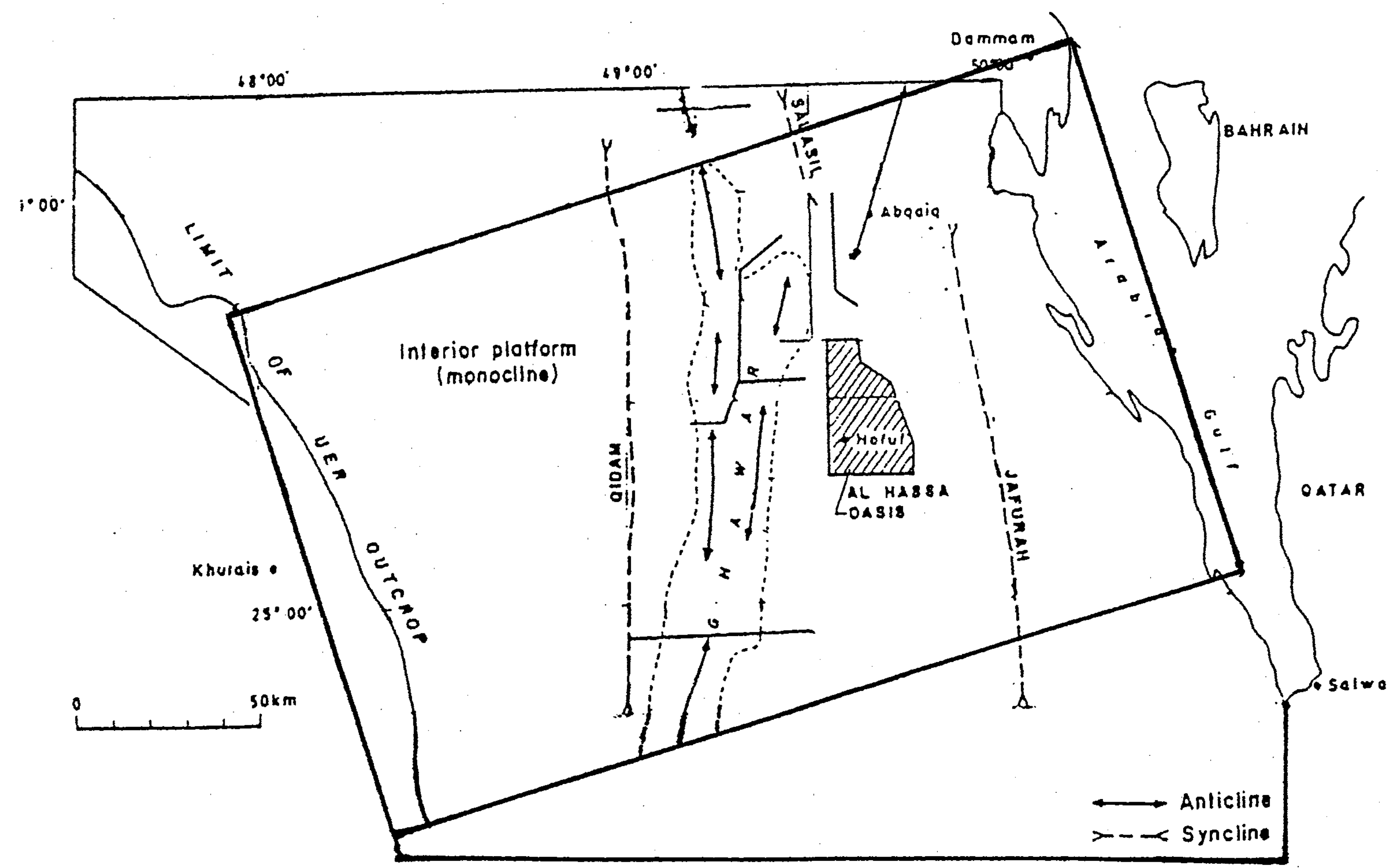


FIGURE VIII. GENERAL LOCATION MAP OF THE STUDY AREA extended groundwater study area was oriented along a northeasterly axis according to the direction of the groundwater flow in the region. A cross section showing the extended groundwater study area is presented in *Figure IX*.

The groundwater model contained 14 rows and 33 columns. The rows and columns were equally spaced at 9.6 km which gives a width of about 134 km and a length of 317 km. Constant head boundaries were established at the eastern border of the groundwater model to represent the coastal zone in both layers.

The finite-difference model required the following information for each cell in the grid: i)the initial head of the Neogene-Dammam aquifer, ii)the initial head in the Umm-Er-Radhuma aquifer; iii)the elevation at the bottom of the Dammam-Neogene aquifer; iv)the vertical thickness of the Rus aquitard which separates the two aquifer layers; v)the elevation at the bottom of the Umm-Er-Radhuma aquifer; and finally vi)the elevation at the top of the Umm-Er-Radhuma aquifer.

The Steady State Calibration

A calibration process was used to test the regional groundwater model and estimate the unknown parameters required for the model (transmissivity, thickness of aquifer, piezometric head). Calibration of the groundwater flow model implied reproducing the pre-irrigation piezometric heads in

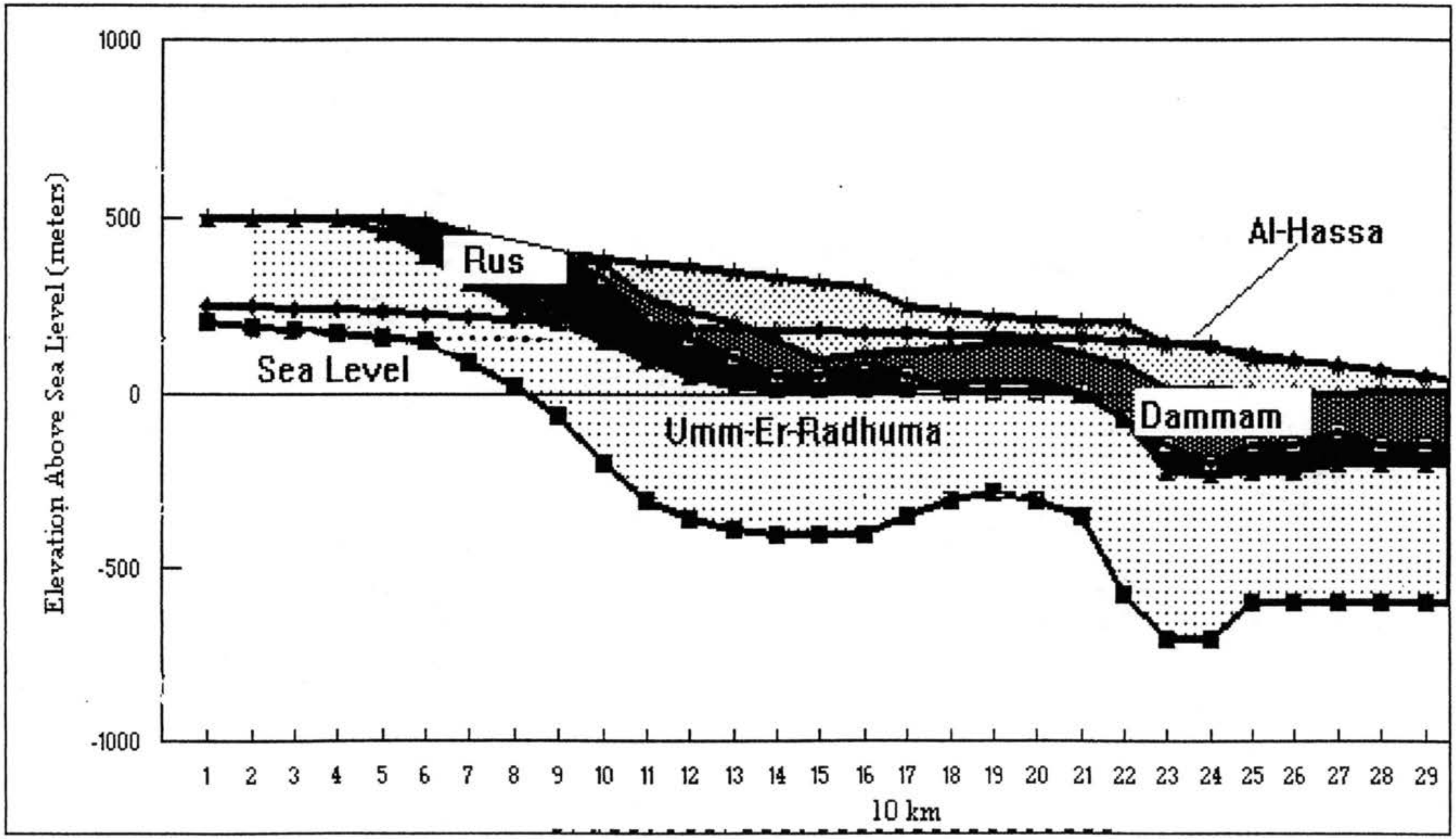


FIGURE IX. A CROSS SECTION SHOWING THE EXTENDED GROUNDWATER STUDY AREA the study area given the estimated natural discharge from Al-Hassa springs and the natural recharge. The calibration process was done by varying the values of the hydraulic conductivity in each grid until the steady state reached by the model matched the initial piezometric head contour lines of the regional aquifer system. The steady state equilibrium of a groundwater system was reached when water inflow and outflow at all point were equal.

The estimated parameters from the steady state calibration were then used as inputs to evaluate the hydraulic response of the multi-groundwater-aquifer system to existing or proposed rate of pumping in the study area.

The Transient Calibration

The aquifer system is called transient when the rates of inflow and outflow at any point in the system are not constant over time. The transient state occurs when the system is subjected to external stresses such as high levels of water extraction.

The finite-difference model was then used to simulate the response of the multi-aquifer system to different pumping rates over a 100 year period. The groundwater model provided estimates of the piezometric head for each cell in each aquifer for each year.

Regression Analysis

The resulting piezometric heads in both layers were regressed against the annual discharge from the study area to quantify the effect of irrigation pumping from the study area on the aquifer level. The impact of pumping from the study area on aquifer levels outside the study area was measured in terms of the average head at the Rus window. The Rus window was selected because the regional aquifer system is interconnected at this point and because the natural gradient is higher at the Rus window than the study area. The general forms of the regression functions was as follows:

$$H_{h\ t} = f(H_{h\ t-1},\ H_{r\ t-1},\ Q_{h\ t-1})$$

$$H_{r\ t} = f(H_{r\ t-1},\ Q_{h\ t-1})$$

where,

$H_{h\ t}$ = predicted piezometric head in the study area in time t, measured in meters (m).

$H_{h\ t-1}$ = predicted piezometric head in the study area in time t-1, measured in meters (m).

$H_{r\ t-1}$ = predicted piezometric head in the Rus window in time t-1, measured in meters (m).

$H_{r\ t}$ = predicted piezometric head in the Rus window in time t, measured in meters (m).

Q_h = pumping rate in the study area, measured in million cubic meters (MCM).

CHAPTER IV

RESULTS OF THE STUDY

The results of the Linear-Dynamic programming approach are illustrated and discussed in this chapter as follows: i)results of the Linear Programming Model; ii) results of the Finite-Difference Groundwater Model; and iii)results of the Dynamic Programming Model.

Results of the Linear Programming Model are presented as follows: i)the base model; ii)validation of the base model; iii)the base model with various combinations of irrigation development; and iv)the effect of projected population growth. Results of the Finite-Difference Groundwater Model are presented as follows: i)steady state calibration; ii)transient state calibration; and iii)regression analysis. Results of the Dynamic Programming Model are presented in terms of optimal plan decisions using different irrigation systems.

Linear Programming Model

Results of the Base model

The base year model was developed to simulate the initial market structure in the study area. Excess demand and supply curves were established and set according to conditions in the study area. The maximized net social benefits generated by the base model solutions showed *the total returns* over *the variable costs*. The average data of 1985-1990 was used in the base model.

i. Surface Irrigation System (SRIS)

Results of the base model with a surface irrigation system are presented in *Table XXVII*. The solution of the base model using a surface irrigation system shows very close results to the actual data in the study area. *The objective function* was maximized at the level of 874 million Riyals, which reflects the net social benefits (NSB) for the entire country. Consumers and producers outside the study area will be better off because of the responsive change of national imports or exports to irrigation levels in the study area. Consumer and producer surplus created by production from the study area was 28 million Riyals. Consumer and producer surplus generated in the study area was calculated as the difference between the national NSB and NSB generated outside the study area.

Total crop area developed in the study area was found to be 8338 hectares. This crop area required about 235 MCM of the water supply annually. Most crop production activities came to the final solution at their maximum levels. However, some of the crops which had been produced in the area did not enter

Table XXVII

BASE MODEL PRODUCTION, TRADE, AND EQUILIBRIUM PRICES WITH THE SURFACE IRRIGATION SYSTEMS

Crops	Al-Hassa Area Land Area (ha)	Production (tons)	Net Import (tons)	National Net Export (tons)	Prices (Sr/ton)
a. winter crops					
Wheat	0	56462		1824682	2018
Tomato	274	10800	68616		862
Potato	107	2084	44107		946
Eggplant	66	1580	2275		1486
Squash	44	951	2375		1375
Cucumber	29	1328	5831		1318
Dry Onion	103	1015	124310		1051
Carrot	80	1324			715
b. Summer Crops					
Tomato	105	4792	62054		883
Potato	0	714	60140		946
Eggplant	33	1162	1957		1482
Squash	67	2283	5602		1392
Watermelon	161	1777	4443		1279
Okra	69	529	1730		3622
Cucumber	53	2492	6684		1319
Sorghum	0				1975
c. Perennial Crops					
Date Palm	7636	44524		23245	2993
Alfalfa	0	4945			1021

the final solution such as wheat, summer potatoes, sorghum, and alfalfa. These crops were less profitable in comparison to the other crops which compete for the same limited resources. Producing one hectare of wheat would lower the annual NSB by 991 Riyals, 982 Riyals if producing a hectare of summer potatoes, and 3739 Riyals if producing a hectare of alfalfa.

Activities for net import and net export for the respective crops came into the solution at their upper limits. Each crop may either be imported or exported. Normally imported crops are tomato, potato, eggplant, squash, cucumber, dry onion, watermelon, and okra. Crops which have been exported are wheat and date palm. Crops such as carrots, sorghum, and alfalfa are neither exported from nor imported into Saudi Arabia.

The equilibrium prices of the respective crops were at the wholesale level. The estimated equilibrium prices for all crops were within 5 percent of the actual prices.

Validation of the Base Model

Validation of the base model means simulating the actual market behavior of the base year data. Simulating the actual market behavior is a key element to get sound and reliable results of the study. Validation of the model was used also to: i)ensure the consistency of the available data and structure of the model; and ii)ensure the accuracy of the long term results of the model.

Inconsistency between the findings of the model and the actual data can occur for one or more of the following reasons: i)the model does not include all the constraints that influence the producers' decisions; ii) the available data are not precise enough; or iii) producers do not base their production decisions on complete or accurate information.

Duwais (1990) stated that validation of a sector model begins with a series of comparisons between the findings of the model and the actual data. Comparisons are most often made on crop production, crop area, and crop prices. A consensus has not been reached on the statistical measures that could be used to evaluate the goodness of fit of a sectoral model. However, measures such as the percentage absolute deviation (PAD) and the mean absolute deviation (MAD) are often used for this purpose.

In this study, the percentage absolute deviation (PAD) was applied to validate the base model in the study area,

$$PAD = \sum_j |X^r_j - X^s_j| / \sum X^r_j$$

where,

X^r_j = real data of x variable in j product.

X^s_j = simulated data of x variable in j product.

The validation process was applied only to the base model with surface irrigation because the available data reflect the extensive use of this system.

The comparison of results between the actual and simulated crop production and crop area are respectively presented in *Tables XXVIII and XXIX*. The PAD value shows a great fit of the crop production and crop area to the real data. The PAD test for the crop production and crop area is applied only to the crop activities which entered the solution of the base model.

Trade is another variable which shows a perfect fit to the actual data as presented in *Table XXX*. Derived prices also fit the actual data well as the PAD value is only 0.91 percent, *Table XXXI*.

ii. Sprinkler Irrigation System (SPIS)

The same model with sprinkler irrigation system generated a maximum *objective function* value of 869 million Riyals, which was less than that for the SRIS. Consumer and producer surplus generated from the study area was 22 million Riyals. This crop area would require 193 MCM per year. This was less than the annual amount of water required by the SRIS, reflecting the higher irrigation efficiency of the SPIS. The change in efficiency did change the crop mix. Crops such as summer potatoes, sorghum, wheat, and alfalfa came into the solution. Winter potatoes, on the other hand, did not enter to the solution.

Using SPIS made domestic production of some crops more profitable compared to importing. Crops such as summer squash watermelon, eggplant, okra, and summer cucumber were produced

TABLE XXVIII

VALIDATION OF PRODUCTION ESTIMATES IN THE STUDY AREA

(TONS)

Crop	Real Crop Production	Simulated Production	Absolute Deviation
a. Winter Crops			
Wheat	56462	0	56462
Tomato	10800	10800	0
Potato	2084	2084	0
Eggplant	1580	1580	0
Squash	951	951	0
Cucumber	1328	1328	0
Dry Onion	1015	1015	0
Carrot	1324	1324	0
b. Summer Crops			
Tomato	4792	4792	0
Potato	1777	0	1777
Eggplant	714	714	0
Squash	1162	1162	0
Watermelon	2283	2283	0
Okra	529	529	0
Cucumber	2492	2492	0
c. Perennial Crops			
Date Palm	44524	44524	0
Alfalfa	4945	0	4945
Total	138762		63184

TABLE XXIX

VALIDATION OF CROP AREA ESTIMATES IN THE STUDY AREA

(HECTARES)

Crop	Real Crop Area	Simulated Area	Absolute Deviation
a. Winter Crops			
Wheat	13728	0	13728
Tomato	274	274	0
Potato	107	107	0
Eggplant	66	66	0
Squash	44	44	0
Cucumber	29	29	0
Dry Onion	103	103	0
Carrot	80	80	0
b. Summer Crops			
Tomato	105	105	0
Potato	99	0	99
Eggplant	33	33	0
Squash	67	67	0
Watermelon	161	161	0
Okra	69	69	0
Cucumber	53	53	0
c. Perennial Crops			
Date Palm	7636	7636	0
Alfalfa	482	0	482
Total	23136		14309

TABLE XXX

VALIDATION OF ESTIMATED TRADE

(HUNDRED TONS)

Crop	Real Trade	Simulated Trade	Absolute Deviation
a. Winter Crops			
Wheat	18247	18247	0
Tomato	686	686	0
Potato	441	441	0
Eggplant	23	23	0
Squash	24	24	0
Cucumber	58	58	0
Dry Onion	1243	1243	0
b. Summer Crops			
Tomato	621	621	0
Potato	601	601	0
Eggplant	20	20	0
Squash	56	56	0
Watermelon	44	44	0
Okra	17	17	0
Cucumber	67	67	0
c. Perennial Crops			
Date Palm	232	232	0
Total	22380		0
PAD	0		

PAD = percentage absolute deviation

TABLE XXXI

VALIDATION OF ESTIMATED CROP PRICES

(SR/TON)

Crops	Real Crop Price	Simulated Crop Price	Absolute Deviation	PAD Percent
a. Winter Crops				
Wheat	2000	2018	18	0.90
Tomato	889	862	27	3.04
Potato	946	946	0	0.00
Eggplant	1486	1486	0	0.00
Squash	1404	1374	30	2.14
Cucumber	1327	1318	9	0.68
Dry Onion	1069	1051	18	1.68
Carrot	745	715	30	4.03
b. Summer Crops				
Tomato	889	883	6	0.67
Potato	946	946	0	0.00
Eggplant	1486	1482	4	0.27
Squash	1404	1392	12	0.85
Watermelon	1279	1279	0	0.00
Okra	3640	3622	18	0.49
Cucumber	1327	1319	8	0.60
Sorghum	1958	1975	17	0.87
c. Perennial Crops				
Date Palm	3000	2993	7	0.23
Alfalfa	1021	1021	0	0.00
Total	26816		204	
PAD				0.91 %

PAD = percentage absolute deviation

in the study area. Detailed results of the base model using SPIS are presented in *Table XXXII.*

iii. Trickle Irrigation System (TRIS)

The objective function of the base model using a trickle irrigation system was maximized at 867 million Riyals. The consumer and producer surplus generated in the study area was 21 million Riyals. The annual water use to develop 8338 hectares would be only 147 MCM per year because of the superior water efficiency of the TRIS over the other irrigation systems.

The crop production mix with a trickle irrigation system was different than with sprinkler or surface systems. Importing some crops becomes costly compared to domestic production. The TRIS allowed production of more water intensive crops such as summer tomatoes, summer cucumber, watermelon, annual eggplant, okra, and annual squash at a lower cost than the other systems. Consequently, the equilibrium prices of these crops were less than with the other systems and imports of these crops were reduced. *Table XXXIII* presents detailed results of the base model using TRIS.

Base Model Solutions By Irrigation System

Selected results of the base models for the three irrigation systems are compared in *Table XXXIV*. The results show the surface irrigation system generated the highest consumer and producer surplus over variable costs. However,

Table XXXII

BASE MODEL PRODUCTION, TRADE, AND EQUILIBRIUM PRICES WITH THE SPRINKLER IRRIGATION SYSTEMS

	Al-Hassa Area		National		
Crops	Land Area (ha)	Production (ton)	Net Import (ton)	Net export (ton)	Prices (SR/ton)
a. Winter Crops					
Wheat	142	584		1825267	2018
Tomato	274	10785	68616		866
Potato	0	0	44107		946
Eggplant	160	3846	0		1423
Squash	44	953	2375		1384
Cucumber	29	1345	5831		1322
Dry Onion	1969	19414	105920		1051
Carrot	80	529			729
b. Summer Crops					
Tomato	755	34519	36476		860
Potato	215	3861	58047		928
Eggplant	123	2667	0		1429
Squash	432	7448	0		1312
Watermelon	474	6721	0		1221
Okra	410	3153	0		3422
Cucumber	140	6635	0		1306
Sorghum	17	207			1889
c. Perennial Crops					
Date Palm	5781	33703		2324	3000
Alfalfa	423	4340			1021

Table XXXIII

BASE MODEL PRODUCTION, TRADE, AND EQUILIBRIUM PRICES WITH THE TRICKLE IRRIGATION SYSTEMS

	Al-Hassa Area			National	
Crops	Land Area (ha)	Production (ton)	Net Import (ton)	Net Export (ton)	Price (SR/ton)
a. Winter Crops					
Wheat	0	0		1824682	2018
Tomato	1619	63724	20274		860
Potato	107	2079	44107		946
Eggplant	160	3846	0		1433
Squash	153	3316	0		1370
Cucumber	29	1345	5831		1315
Dry Onion	2397	23634	101697		1051
Carrot	80	529			710
b. Summer Crops					
Tomato	1553	71003	0		859
Potato	1610	28916	33002		928
Eggplant	123	2667	0		1430
Squash	432	7448	0		1342
Watermelon	474	6721	0		1226
Okra	410	3153	0		3436
Cucumber	194	9194	0		1307
Sorghum	17	207			1873
c. Perennial Crops					
Date Palm	4003	23337		23245	3011
Alfalfa	160	1642			1021

TABLE XXXIV

BASE MODEL COMPARISON BY IRRIGATION SYSTEM

Variable	Unit	Surface System	Sprinkler System	Trickle System
Objective Value	million SR	874	869	867
Crop Production	000 ton	76	144	254
Crop Area	00 ha	88	115	135
Net Imports	million SR	385	307	204
Net Exports	million SR	3682	3683	3682
Water Use	MCM	235	193	147
Water Return	SR/cu m	3.72	4.50	5.90

this required more irrigation water and would result in a more rapid decline in the water table than would the other systems. Net return per unit of water was the lowest with SRIS because of the lower irrigation efficiency. The trickle irrigation system generated the highest net return per unit of water, reflecting the superior irrigation efficiency.

Total crop production could be increased with trickle irrigation systems which in turn would reduce imports. Increased efficiency of water use can either increase the productivity of land or allow more land area to be irrigated with the same volume of water.

Application of the Base Model

The validated base model was then used to estimate what the consumer and producer surplus would be when the state variables were altered by: i)reduced water table; ii)change in the irrigated area; iii)change in the number of drilled wells; iv)change in the annual water use; and v)increased population. Consumer and producer surplus was maximized for each possible combination of these state variables.

Pumping Costs

The cost of pumping is an important variable in determining the net social benefits. The cost of pumping was calculated with different numbers of wells or spacing and depth to static water table or piezometric head. The selected numbers of wells in the study area were: 150, 300, 450, 600, and 750 wells. In each case, the wells were assumed to be uniformly spread over the study area. Five levels of the static water table were assumed. These represented cases where the static water table was: 0, 148, 296, 444, and 592 meters from the ground surface.

Confined Aquifer VS. Unconfined Aquifer

The available data collected from wells penetrating the Umm-Er-Radhuma aquifer (UER) in the study area show the following: i)depth to the top of aquifer averages 250 meters; ii)depth from top of the aquifer to the bottom of the well screen is 100 meters; iii)the static water table is 40 meters below the ground surface; iv) the dynamic water table is 45 meters below the surface; and v)the well discharge is 1200 gallons per minute (GPM).

Total dynamic head was simulated using the pumping drawdown models developed by *Dawson and Istok (1991)*. The objective of the simulation process was to generate data which could be used to empirically relate the pumping drawdown to the rate of pumping and the length of the pumping period in the study area. Drawdown was simulated for the three different conditions of the aquifer which could be encountered in the study area: i)a confined aquifer with a partial penetrating well *(PPCA)*; ii)an aquifer undergoing conversion from a confined to an unconfined aquifer *(CCUNA)*; and iii)an unconfined aquifer with a partial penetrating well *(PPUCA)*.

The simulations were made at different levels of: aquifer penetration, pumping time, pumping rate, and well densities or spacing. The generated regression equation for each of the different aquifer types showed a 99 percent fit to the computer generated data. The estimated regression equations for the various types of aquifer are shown below:

Partial penetration confined aquifer,

$$Ln\ PDD = 3.01 + 0.08\ Ln\ T - 0.01\ Ln\ T^2 - 0.64\ Ln\ PEN + 0.07\ Ln\ PEN^2 + 1.00\ Ln\ Q - 0.08\ Ln\ RD - 0.02\ Ln\ RD^2 + 0.0005\ Ln\ T^3 + 0.01\ Ln(T \times PEN) + 0.002\ Ln(T \times PEN^2) - 0.01\ Ln(T \times RD) + 0.005\ Ln(T \times RD^2) - 7E\text{-}6\ Ln(PEN \times Q) + 0.02\ Ln(PEN^3) + 0.02\ Ln(PEN \times RD^2).$$

Conversion from Confined to Unconfined Aquifer,

$$PDD = -0.106 + 0.004\ T - 2.1E\text{-}5\ T^2 - 6.5E\text{-}5\ RAD + 22.636\ Q + 3.9E\text{-}6\ RD - 3.9E\text{-}8\ (T \times RD) + 8.7E\text{-}9\ (RD \times RAD) - 0.044\ (RD \times Q) + 3.3E\text{-}7\ (RAD \times T) - 0.0006\ (RAD \times Q) + 0.0167\ (T \times Q) + 3.0E\text{-}8\ (T^3) + 2.7E\text{-}13\ (RD^2) + 0.00003\ (Q \times RD^2).$$

partial penetration unconfined aquifer,

$$PDD = 2.95 + 0.01\ T - 0.76\ PEN + 1.00\ Q + 0.06\ RD + 0.01\ (T \times PEN) - 0.04(T \times RD) + 0.02\ PEN^2 - 0.06\ RD^2 + 0.01(T \times RD^2) + 0.02(PEN \times RD^2)$$

Where,

PDD = predicted well drawdown, measured in meters.

T = time of pumping, measured in seconds.

PEN = penetration level, measured in meters.

RD = radial distance from the pumping well to a point on the cone of depression, measured in meters.

RAD = radial distance from the pumping well to the edge of the confined zone, measured in meters.

Q = pumping rate, measured in cubic meters per second.

Figures X-XII respectively compare the computed drawdown with the simulated drawdown for the different types of aquifer. *Table XXXV* presents the estimated pumping drawdown at different levels of initial water table and well density in the study area.

The above regression equations were entered into a pumping cost model developed by *Stoecker (1994)* to calculate the cost of pumping associated with different aquifer states and well densities. Detailed results of the calculated pumping costs for the respective irrigation systems are presented in *Tables XXXVI, XXXVII, and XXXVIII*.

The cost of pumping increases with an increase in pressure at the well head. Thus, the cost of pumping a unit of water is higher when sprinkler irrigation is used because it requires more pressure at the well head than does a surface system or a trickle system. The pressures for the different irrigation systems are: 35 PSI for sprinkler, 12 PSI for trickle, and 10 PSI for surface.

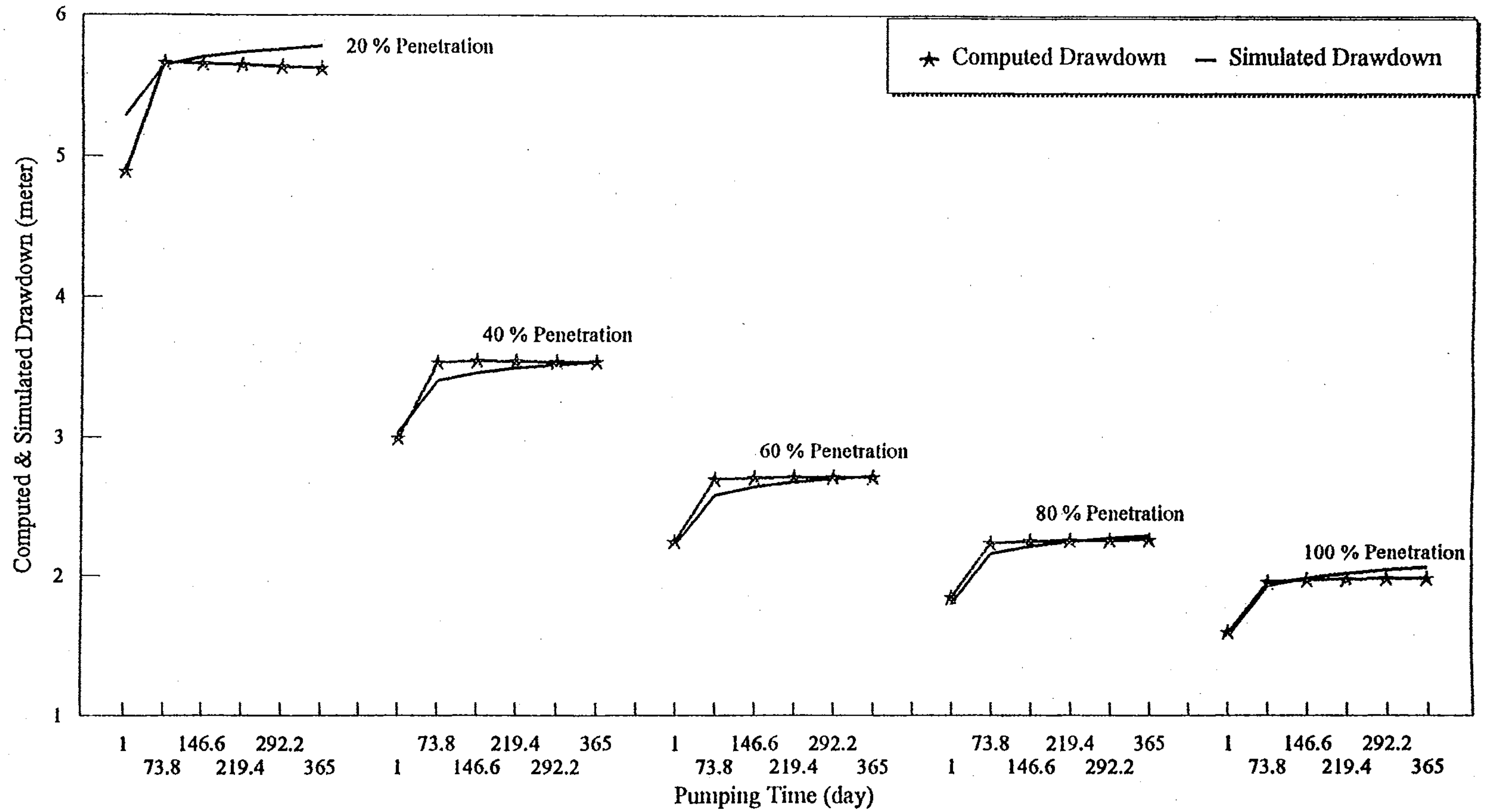


FIGURE X. COMPUTED AND SIMULATED DRAWDOWNS FOR PARTIAL PENETRATION INTO A CONFINED AQUIFER IN AL-HASSA AREA

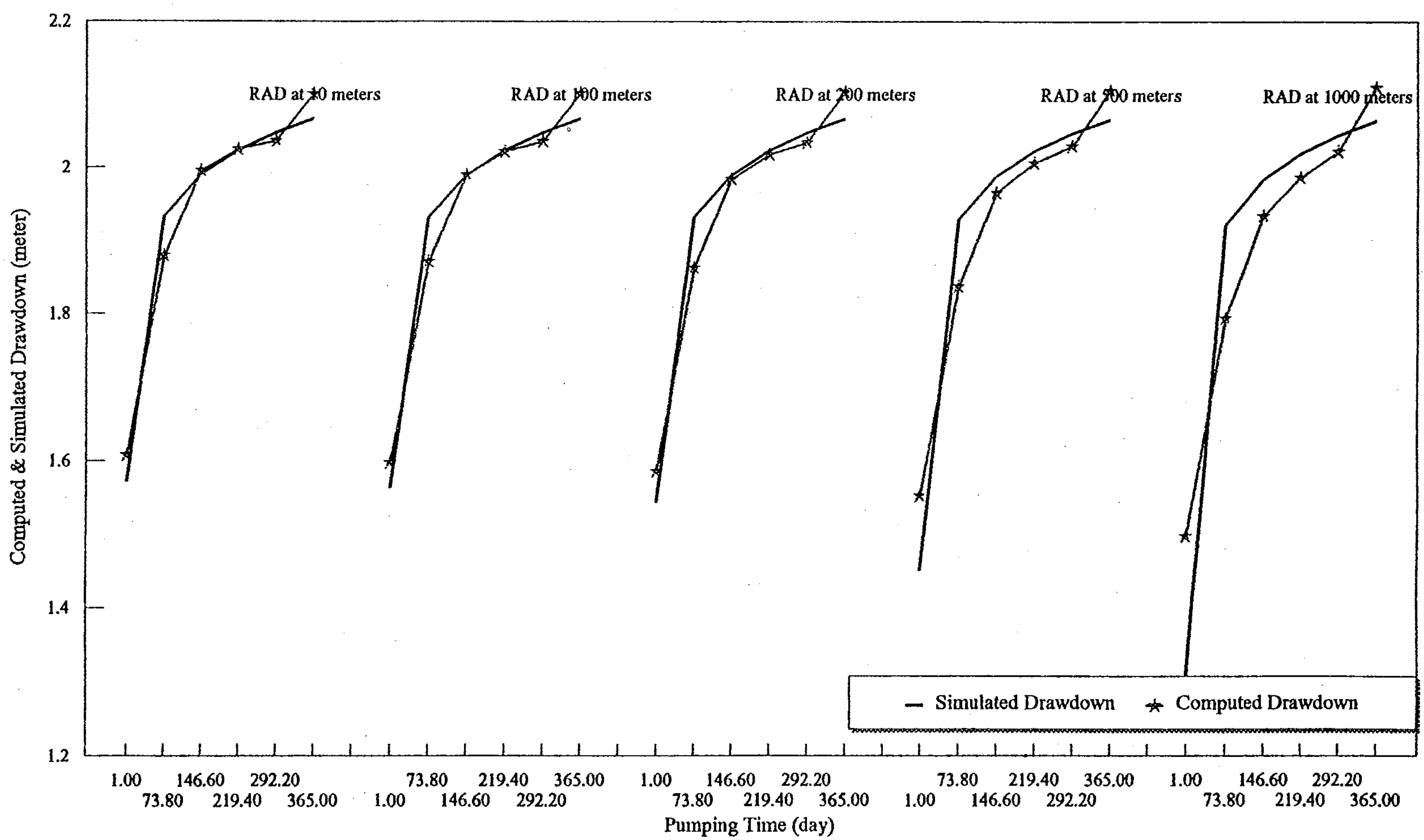


FIGURE XI. COMPUTED AND SIMULATED DRAWDOWNS FOR THE AQUIFER UNDERGOING CONVERSION FROM A CONFINED TO AN UN-CONFINED STATES IN AL-HASSA AREA

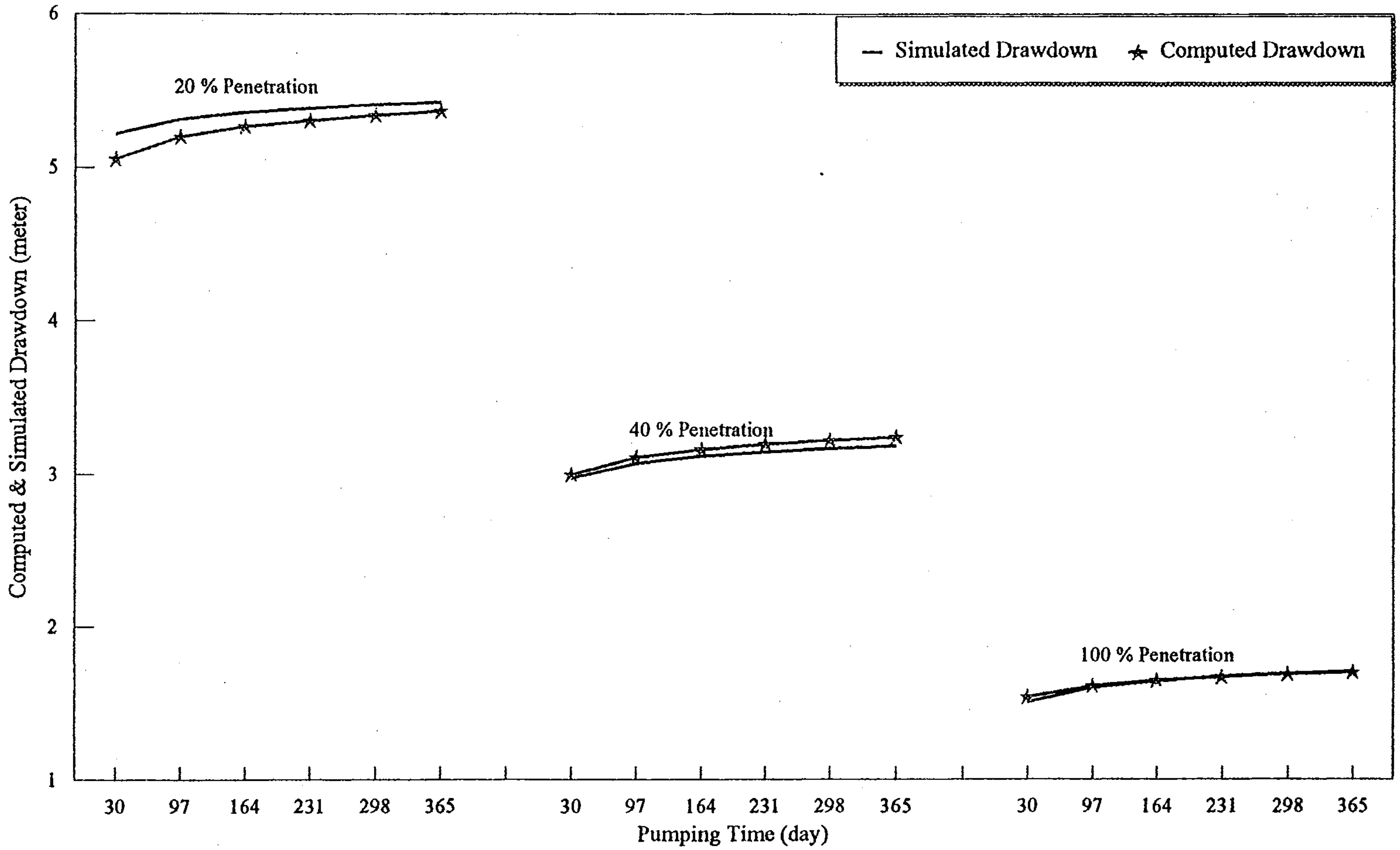


FIGURE XII. COMPUTED AND SIMULATED DRAWDOWNS FOR PARTIAL PENETRATION INTO AN UN-CONFINED AQUIFER IN AL-HASSA AREA

TABLE XXXV

THE ESTIMATED PUMPING DRAWDOWNS FOR THE UMM-ER-RADHUMA AQUIFER, AT 1200 GPM PUMPING RATE

(METER)

Number of	Depth to Static Water Table (m)				
Wells	148	296	444	592	700
150	16	16	14	23	31
300	17	16	14	23	32
450	17	16	14	23	32
600	17	16	14	23	32
750	18	16	14	23	32

TABLE XXXVI

PUMPING COST WITH THE SURFACE SYSTEM.

(SR/0000 CU METERS)

Number of Wells	Depth to Static Water Table (m)				
	148	296	444	592	700
150	381.66	700.21	1017.94	1359.05	1622.00
300	382.79	705.22	1023.04	1368.01	1623.37
450	382.28	702.83	1023.04	1365.45	1621.55
600	382.41	701.11	1020.65	1363.23	1619.65
750	383.31	699.96	1018.76	1359.75	1618.02

TABLE XXXVII

PUMPING COST WITH THE SPRINKLER SYSTEM.

(SR/0000 CU METERS)

Number of Wells	Depth to Static Water Table (m)				
	148	296	444	592	700
150	412.19	730.67	1048.44	1389.53	1652.70
300	413.32	735.90	1053.70	1398.70	1654.07
450	412.71	733.40	1053.70	1396.08	1652.19
600	412.81	731.60	1051.23	1393.81	1650.25
750	413.75	730.41	1049.29	1390.24	1648.58

TABLE XXXVIII

PUMPING COSTS WITH THE TRICKLE SYSTEM.

(SR/0000 CU METERS)

Number of Wells	Depth to Static Water Table (m)				
	148	296	444	592	700
150	404.56	723.05	1040.81	1381.91	1645.02
300	405.69	728.23	1046.04	1391.03	1646.39
450	405.10	725.76	1046.04	1388.42	1644.53
600	405.21	723.98	1043.59	1386.16	1642.60
750	406.14	722.79	1041.66	1382.62	1640.94

The Projected PLP Model

Projections of the domestic demand and supply from outside the study area were made to estimate the net social benefits that could be obtained by using the groundwater in the future. These projections were made for the years 2005, 2020, 2035, and 2050. The projected PLP model was used to estimate the maximum net social benefits that could be obtained with each level of annual water use in combination with each possible irrigated area, irrigation well, and aquifer level. Separate PLP models were developed for each type of irrigation system. Crop production from outside the study area was assumed to grow at about 2 percent per year. Trade and demand were assumed to grow at the population growth rate as shown in Table XXVI.

Results of the Projected PLP Models

Estimates of the maximum net social benefits (NSB) from the study area were obtained for the years 1990, 2005, 2020, 2035, and 2050 for the selected aquifer levels(0, 148, 296, 444, and 592 meters from the surface) in combination with each possible number of wells (0, 150, 300, 450, 600, and 750) and each possible irrigated area (0, 4000, 8000, 12000, 16000, and 20000 hectares).

The maximized net social benefits in the study area were calculated as follows:

$$NSB^{y}_{hlqa} = NSB^{y}_{nlqa} - NSB^{y}_{olqa} - FC^{y}_{lqa}$$

where,

NSB^{y}_{hlqa} = net social benefits from the study area in year y, given level of land area (l), aquifer state (q), and annual water use (a).

NSB^{y}_{nlqa} = maximized national net social benefits in year y, given level of land area (l), aquifer state (q), and annual water use (a).

NSB^{y}_{olqa} = maximized net social benefits outside the study area in year y, given level of land area (l), aquifer state (q), and annual water use (a).

FC^{y}_{lqa} = annual amortized investment cost (excluding well cost) in year y, given level of land area (l), aquifer state (q), and annual water use (a).

y = 1990, 2005,..., 2050 year.

l = 4000, 8000,..., 20000 hectares.

q = 0, 148,..., 700 meters below ground surface.

a = 70, 140,..., 560 MCM of water.

Annual amortized cost is calculated as follows:

$$APW_e = C_e \frac{(1+i)^n}{(1+i)^n - 1} * i$$

where,

APW_e = annual amortized cost of a given element (e).

C_e = initial investment cost of a given element (e).

i = discount rate.

n = expected life of a given element.

Capital Costs

The two main elements of the capital costs are :i)initial investment costs; and ii)restaging costs. The initial investment costs were divided in the cost per well and the cost per hectare for the irrigation distribution. The cost per well includes the cost of drilling, the engine, and pump assembly and installation. The cost per hectare includes installation cost of a particular irrigation system (surface, sprinkler, and trickle), and drainage system. The investment needed to install the irrigation systems measured in SR/ha averaged about 2178 for surface irrigation, 3475 for sprinkler irrigation, and 6950 for trickle irrigation (Eisenhauer et al., 1994). The investment needed to install the surface drainage system averaged about 1297 SR/ha (Pavelis, 1987). It was assumed that a well could be restaged when the water declined to a point where the pump could not be operated. Restaging included the costs of drilling the existing well to a greater depth, extending the well screen, pipe column, and adding more bowls to the well.

Table XXXIX presents initial investment cost per well; *Table XL* presents restaging costs. The calculated costs are presented at different depths of the static water table (aquifer states) and different well densities.

The maximum net social benefits outside the study area in terms of million Riyals were found to be equal to: 846 in year 1990, 1030 in year 2005, 1189 in year 2020, 1364 in year 2035, and 1642 in year 2050.

There were potentially 625 solutions for each irrigation system. However, it was not necessary to obtain all solutions. *Tables XLI-XLVI* present the results for selected solutions in

TABLE XXXIX

INVESTMENT REQUIRED TO ESTABLISH AN IRRIGATION WELL

(SR/WELL)[1]

Static Water Table (m)	Number of Wells (well)				
	150	300	450	600	750
0	991466	991466	992566	993666	994766
148	1116304	1113004	1114104	1115204	1116304
296	1514245	1510945	1510945	1512045	1513145
444	1952461	1946961	1948061	1949161	1951361
592	2296507	2296507	2297607	2298707	2299807

Sources: Abunayyan Sons Co. 1994; and MOAW, 1994.
1. Costs per well are not discounted.

TABLE XL

INVESTMENT REQUIRED TO RESTAGE AN EXISTING IRRIGATION WELL

(SR/WELL)[1]

Static Water Table (m)	Number of Wells (well)				
	150	300	450	600	750
0	0	0	0	0	0
148	241304	238004	239104	240204	241304
296	639245	635945	635945	637045	638145
444	777461	771961	773061	774161	776361
592	734007	734007	735107	736207	737307

Sources: Abunayyan Sons Co. 1994; and MOAW, 1994.
1. Restaging costs per well are not discounted.

TABLE XLI

ANNUAL NET SOCIAL BENEFITS WITH EXISTING WELLS FROM USING 70 MCM OF WATER IN YEAR 2005 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	7690	7170	5291	1099	1024	773
	450	4028	3628	1709	575	518	244
	750	127	-273	-2192	18	-39	-313
12000	150	5782	5922	3314	826	846	473
	450	3890	8250	4173	556	1179	596
	750	-11	4339	262	-2	620	37
20000	150	3103	2244	-3042	443	321	-435
	450	1212	4612	-13	173	659	-2
	750	-2689	701	-3915	-384	100	-559

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = engine cost + bowl cost + system cost + drainage cost. Cost of drilling the well is not included.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE XLII

ANNUAL NET SOCIAL BENEFITS WITH EXISTING WELLS FROM USING 280 MCM OF WATER IN YEAR 2005 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	10220	7510	5291	1041	871	773
	450	9918	4728	1829	710	424	241
	750	6017	827	-2072	431	74	-274
12000	150	9592	7122	4754	886	670	450
	450	27640	16980	10003	987	752	482
	750	24459	14459	6492	874	519	301
20000	150	6913	3444	-1602	639	324	-151
	450	27592	22062	14127	985	788	580
	750	26981	20851	10235	964	745	421

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = engine cost + bowl cost + system cost + drainage cost. Cost of drilling the well is not included.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE XLIII

ANNUAL NET SOCIAL BENEFITS WITH EXISTING WELLS FROM USING 560 MCM OF WATER IN YEAR 2005 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	10220	7510	5291	1041	871	773
	450	9918	4728	1829	710	424	241
	750	6017	827	-2072	431	74	-274
12000	150	9592	7122	4754	886	670	450
	450	28130	16980	10003	967	752	482
	750	30749	14459	6492	853	519	301
20000	150	6913	3444	-1602	639	324	-151
	450	30462	22512	14127	939	719	580
	750	37861	22131	10235	888	568	421

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = engine cost + bowl cost + system cost + drainage cost. Cost of drilling the well is not included.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE XLIV

ANNUAL NET SOCIAL BENEFITS WITH EXISTING WELLS FROM USING 70 MCM OF WATER IN YEAR 2050 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	9145	9485	8156	1306	1355	1165
	450	5533	5804	4474	790	829	639
	750	1632	1902	573	233	272	82
12000	150	7347	8297	5580	1050	1185	797
	450	5365	8996	5878	766	1285	840
	750	1454	5084	1977	208	726	282
20000	150	4669	4619	-777	667	660	-111
	450	2687	5347	712	384	764	102
	750	-1224	1436	-3189	-175	205	-456

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = engine cost + bowl cost + system cost + drainage cost. Cost of drilling the well is not included.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE XLV

ANNUAL NET SOCIAL BENEFITS WITH EXISTING WELLS FROM USING 280 MCM OF WATER IN YEAR 2050 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	11505	10445	8246	1190	1207	1147
	450	10953	7994	5154	719	667	561
	750	7052	4092	1253	467	341	136
12000	150	10947	9797	7200	1036	1006	747
	450	29875	22376	15638	1067	848	734
	750	26194	19714	11897	936	704	538
20000	150	8269	6119	843	783	628	88
	450	29897	25657	18102	1068	916	724
	750	28256	24736	14421	1009	883	541

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = engine cost + bowl cost + system cost + drainage cost. Cost of drilling the well is not included.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE XLVI

ANNUAL NET SOCIAL BENEFITS WITH EXISTING WELLS FROM USING 560 MCM OF WATER IN YEAR 2050 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	11505	10445	8246	1190	1207	1147
	450	10953	7994	5154	719	667	561
	750	7222	4092	1253	478	341	136
12000	150	10947	9797	7200	1036	1006	747
	450	30265	22376	15638	1035	848	734
	750	32684	21114	11897	904	623	538
20000	150	8269	6119	843	783	628	88
	450	32727	25747	18102	1026	856	724
	750	41816	28436	14421	948	669	541

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = engine cost + bowl cost + system cost + drainage cost. Cost of drilling the well is not included.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

terms of returns over average total cost when the wells already exist. The investment costs were amortized. The results are shown without the cost of drilling the wells. These intermediate results are useful because they present an estimate of the returns over average total cost for various levels of aquifer depletion at different points of time.

The investment needed to drill a well has a large effect on net social benefits. The estimated cost of drilling a well in the study area to a depth of 350 meters is about 700 thousand Saudi Riyals, or about 186 thousand US dollars. The investment needed to drill a well represents more than 70 percent of the total fixed cost. During the 15 year period and a well is drilled, the net social benefits will usually be negative. On the other hand, the net social benefits will usually be positive when wells already exist. That is, it generally requires more than 15 years to pay back the cost of the well.

For a given irrigation system, the results show: i)that NSB increases with an increase in annual water use and the irrigated land area. The annual NSB with existing wells are the highest when 560 MCM of water are used on 20000 hectares of land. However, the highest annual rate of water use will give the greatest decline in the aquifer; and ii)the highest one-year NSB occur in year 2050 because of population growth. The NSB for each irrigation system configuration in the year

2050 are nearly twice those in 2005.

Tables XLVII to LII present selected results of the NSB generated from the study area by type of irrigation system, when the cost of drilling wells was included. The return per unit of water used in irrigation is presented in these tables as well. The NSB were mostly negative, implying that most irrigation investments would not be recovered in a 15 year period when the wells must be drilled. In this case, the trickle irrigation system showed the highest net social loss. The surface irrigation system would provide the most net benefits or the least loss if all wells were drilled and it were necessary to recover all costs in a 15 year period.

Solutions of the projected LP models using different irrigation systems provide the first series of input to the dynamic programming model.

The Finite-Difference Groundwater Model

The Finite-Difference Groundwater Model developed *by McDonald and Harbaugh (1980)* was used to estimate the rate at which the water table would be lowered because of pumping in the study area. The estimation process required the following two steps: i)simulate the initial piezometric heads in the study area; and then ii)measure the change in the simulated piezometric heads based on different levels of pumping rates over a 100 year time horizon. The estimated results were

TABLE XLVII

ANNUAL NET SOCIAL BENEFITS FROM USING 70 MCM OF WATER IN YEAR 2005 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	859	339	-1540	123	48	-225
	450	-16463	-16863	-18782	-2352	-2409	-2683
	750	-34025	-34425	-36344	-4861	-4918	-5192
12000	150	-1049	-909	-3516	-150	-130	-502
	450	-16601	-12241	-16318	-2372	-1749	-2331
	750	-34163	-29813	-33890	-4880	-4259	-4841
20000	150	-3727	-4587	-9872	-532	-655	-1410
	450	-19279	-15879	-20504	-2754	-2268	-2929
	750	-36841	-33451	-38067	-5263	-4779	-5438

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = well cost + engine cost + bowl cost + system cost + drainage cost.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE XLVIII

ANNUAL NET SOCIAL BENEFITS FROM USING 280 MCM OF WATER IN YEAR 2005 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	3389	679	-1540	345	79	-225
	450	-10573	-15763	-18662	-757	-1412	-2464
	750	-28135	-33325	-36224	-2014	-2985	-4782
12000	150	2761	291	-2076	255	27	-196
	450	7149	-3511	-10488	255	-155	-505
	750	-9693	-19693	-27660	-346	-708	-1284
20000	150	83	-3387	-8432	8	-318	-798
	450	7101	1571	-6364	254	56	-261
	750	-7171	-13301	-23917	-256	-475	-983

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = well cost + engine cost + bowl cost + system cost + drainage cost.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE XLIX

ANNUAL NET SOCIAL BENEFITS FROM USING 560 MCM OF WATER IN YEAR 2005 IF THE STATIC WATER TABLE AT CURRENT DEPTH

Land Area (ha)	Number of Wells	Net Social Benefits (000 SR)[1] Surface System	Sprinkler System	Trickle System	Water Return (SR/unit)[2] Surface System	Sprinkler System	Trickle System
4000	150	3389	679	-1540	345	79	-225
	450	-10573	-15763	-18662	-757	-1412	-2464
	750	-28135	-33325	-36224	-2014	-2985	-4782
12000	150	2761	291	-2076	255	27	-196
	450	7639	-3511	-10488	263	-155	-505
	750	-3403	-19693	-27660	-94	-708	-1284
20000	150	83	-3387	-8432	8	-318	-798
	450	9971	2021	-6364	307	65	-261
	750	3709	-12021	-23917	87	-308	-983

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = well cost + engine cost + bowl cost + system cost + drainage cost.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE L

ANNUAL NET SOCIAL BENEFITS FROM USING 70 MCM OF WATER IN YEAR 2050 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	2315	2655	1326	331	379	189
	450	-14958	-14688	-16017	-2137	-2098	-2288
	750	-32520	-32250	-33579	-4646	-4607	-4797
12000	150	516	1467	-1251	74	210	-179
	450	-15126	-11496	-14613	-2161	-1642	-2088
	750	-32698	-29068	-32175	-4671	-4153	-4596
20000	150	-2162	-2211	-7607	-309	-316	-1087
	450	-17804	-15144	-19779	-2543	-2163	-2826
	750	-35376	-32716	-37341	-5054	-4674	-5334

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = well cost + engine cost + bowl cost + system cost + drainage cost.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE LI

ANNUAL NET SOCIAL BENEFITS FROM USING 280 MCM OF WATER IN YEAR 2050 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	4675	3615	1416	484	418	197
	450	-9538	-12498	-15337	-626	-1043	-1668
	750	-27100	-30060	-32899	-1793	-2508	-3578
12000	150	4116	2967	369	390	304	38
	450	9384	1884	-4853	335	71	-228
	750	-7958	-14438	-22255	-284	-516	-1006
20000	150	1438	-711	-5987	136	-73	-621
	450	9406	5166	-2389	336	185	-96
	750	-5896	-9416	-19731	-211	-336	-741

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = well cost + engine cost + bowl cost + system cost + drainage cost.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

TABLE LII

ANNUAL NET SOCIAL BENEFITS FROM USING 560 MCM OF WATER IN YEAR 2050 IF THE STATIC WATER TABLE AT CURRENT DEPTH

		Net Social Benefits (000 SR)[1]			Water Return (SR/unit)[2]		
Land Area (ha)	Number of Wells	Surface System	Sprinkler System	Trickle System	Surface System	Sprinkler System	Trickle System
4000	150	4675	3615	1416	484	418	197
	450	-9538	-12498	-15337	-626	-1043	-1668
	750	-26930	-30060	-32899	-1781	-2508	-3578
12000	150	4116	2967	369	390	304	38
	450	9774	1884	-4853	334	71	-228
	750	-1468	-13038	-22255	-41	-385	-1006
20000	150	1438	-711	-5987	136	-73	-621
	450	12236	5256	-2389	384	175	-96
	750	7664	-5716	-19731	174	-134	-741

1) Net social benefits from the study area = national net social benefits less net social benefits outside the study area and fixed cost. Fixed costs = well cost + engine cost + bowl cost + system cost + drainage cost.

2) Return per unit of water = net Social Benefits in the study area / annual water use.

necessary to estimate the transition equations for groundwater in the DP model.

Steady State Calibration

The steady state calibration of the initial heads in the study area required the following inputs: i)the transmissivity of all cells which is a product of hydraulic conductivity and saturated thickness of the given aquifer; ii)the annual discharge from wells in the study area; iii)the annual recharge for the given aquifer; and iv)the storativity coefficients.

Annual discharge was set at about 208.80 MCM which is equivalent to the annual discharge of the natural springs in the study area (Al-Taher, 1987). Estimated *annual recharge* was set at 51.68 MCM for Neogene; 85.71 MCM for Dammam; and 100.59 MCM for Umm-Er-Radhuma, totaling 237.98 MCM (Othman, 1983; WAOSA, 1984). *Storativity* or storage coefficient was set at 2.75^{-2} for Neogene and Dammam, and 4^{-4} for Umm Er Radhuma. The storativity was held constant for each aquifer.

The simulation was necessary to develop and calibrate a preliminary groundwater model. Complete data concerning the elevation, thickness, horizontal and vertical conductivity, piezometric head, and net recharge for each cell in the model were not available. Rather an initial set of estimates for these values were estimated mainly by interpolation from available data. The initial estimates were unlikely to produce an equilibrium set of piezometric heads which matched the known contours given the estimated natural discharge from springs in the study area. Thus, it was necessary to revise the initial parameters until a model was developed which would converge to a steady state that satisfactorily approximated the initial piezometric heads.

The transmissivity of all cells was simulated for each aquifer in the system. Transmissivity of the Neogene-Dammam layer was found to range between 2.93^{-4} m^2/s to 5.17^{-2} m^2/s; and it ranged from 3.17^{-6} m^2/s to 10.87^{-2} m^2/s for Umm-Er-Radhuma. The average transmissivity in the study area was estimated at 7.17^{-2} m^2/s. The estimated transmissivity of all cells in Neogene-Dammam and Umm-Er-Radhuma aquifers is presented in *Tables LX and LXI in the Appendix.*

Figures XIII and XIV present the simulated piezometric heads of the Neogene-Dammam and Umm-Er-Radhuma aquifers.

Transient State Calibration

Tables LIII and LIV present the results of the transient calibration simulation. The results show the change in the average piezometric head in the study area over different annual time horizons. The average piezometric head will rise in both layers at 70 MCM annual rate of pumping, which is less than the actual pumping rate of 208.80 MCM annually. As rate of pumping increases in the study area the average piezometric head in both aquifers will drop by more than 100 meters,

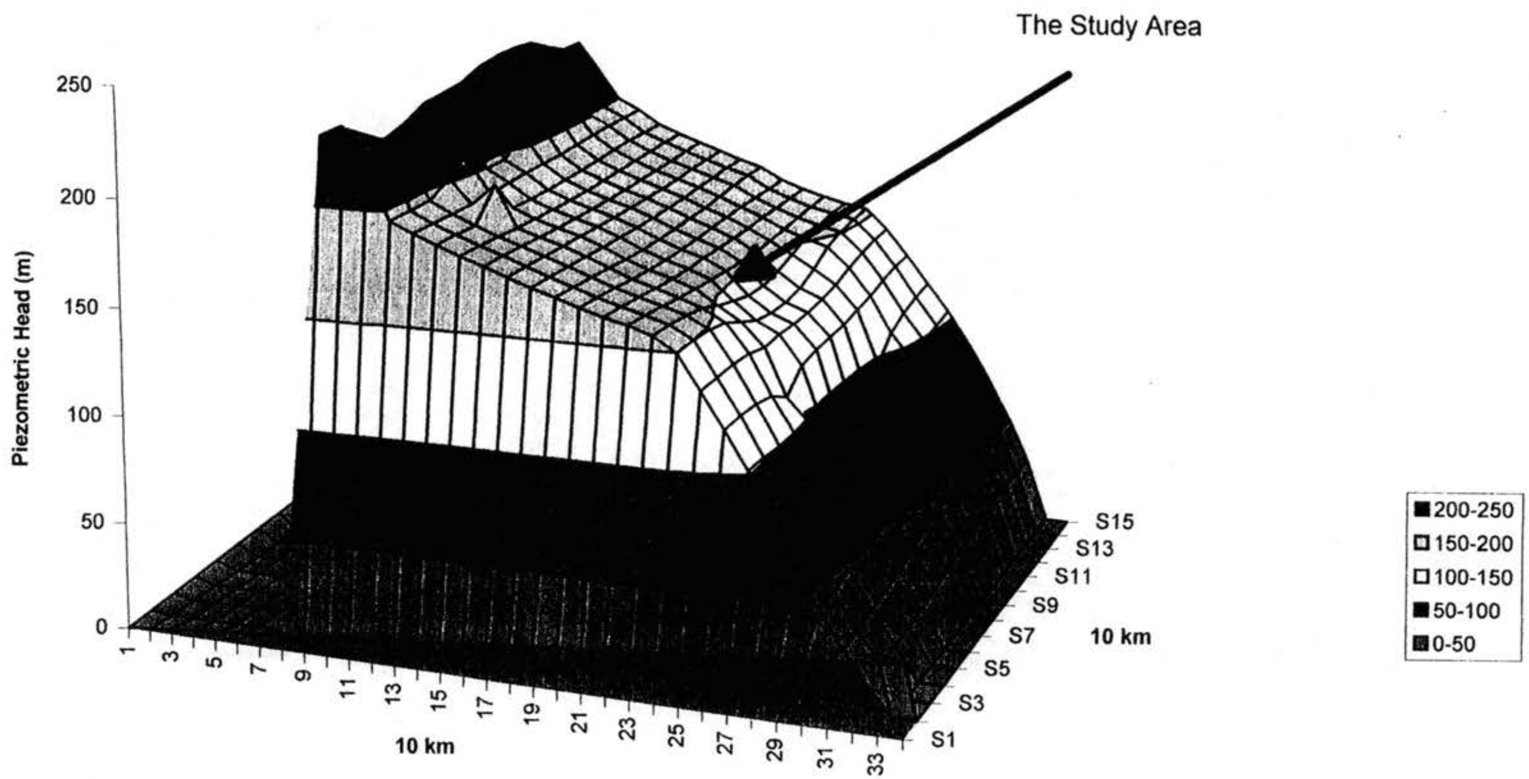


FIGURE XIII. CROSS SECTION SHOWING THE SIMULATED PIEZOMETRIC HEADS IN THE NEOGENE-DAMMAM LAYER

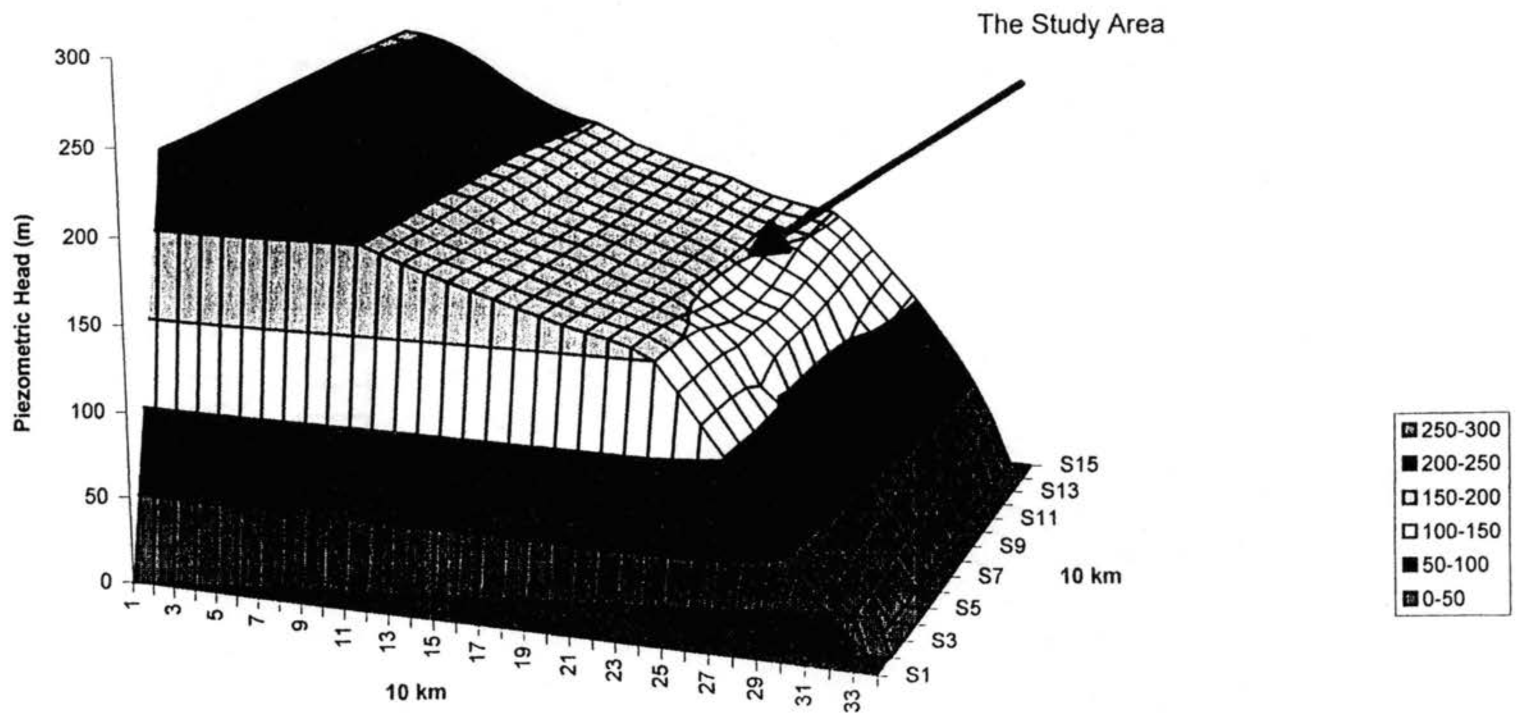


FIGURE XIV. CROSS SECTION SHOWING THE SIMULATED PIEZOMETRIC HEADS IN THE UMM-ER-RADHUMA LAYER

TABLE LIII

AVERAGE PIEZOMETRIC HEADS OVER TIME USING DIFFERENT PUMPING RATES FOR THE NEOGENE-DAMMAM LAYER

(METERS ABOVE SEA LEVEL)

Pumping Time (Years)	Pumping Rate (MCM)		
	70	350	560
1	141	136	132
10	151	125	105
25	157	117	87
50	162	109	67
100	168	94	32

TABLE LIV

AVERAGE PIEZOMETRIC HEADS OVER TIME USING DIFFERENT PUMPING RATES FOR THE UMM-ER-RADHUMA LAYER

(METERS ABOVE SEA LEVEL)

Pumping Time (Years)	Pumping Rate (MCM)		
	70	350	560
1	141	136	132
10	151	125	105
25	157	118	87
50	162	109	67
100	168	94	40

indicating the direct connection between pumping rate and head in the study area.

Regression Analysis

A regression equation was used to measure the relationship between change in the average piezometric head and the rate of pumping in the study area. The estimated regression equation empirically relates the change in the piezometric head of the multi-aquifer system in the study area to the rate of pumping and to the change in the piezometric head at the Rus window where the aquifers are connected. The estimated regression equation was developed as follows:

$$CHGH_{h\ t} = 0.54 - \underset{(59.56)}{0.12\ CHGH_{rh\ t-1}} + \underset{(50.91)}{0.13\ Q_{iht-1}} + \underset{(7.72)}{0.0002\ Q^2_{iht-1}}.$$

where,

$CHGH_{h\ t}$ = change in the average piezometric head in the study area between year t and t-1, measured in meters.

$CHGH_{rh\ t-1}$ = difference between the average piezometric head in the Rus window area (r) and the average piezometric head in the study area in time t-1, measured in meters.

Q_{iht} = annual pumping rate in the study area, measured in MCM.

t = 1,2,..., 100 years.

i = 70, 140,..., 560 MCM.

The estimated regression equation explained 90 percent of the variation of the dependent variables. The T-test values are in parentheses. As expected, the equation indicates the rate of pumping and the change in the average head in the study area are positively related. As the well discharge increases, the more the average head declines in the study area. Withdrawals in the study area were also measured in terms of the change in the average head at the Rus window. However, the more the difference between the heads in the Rus window and study area, the less the current head declines. Water will flow from the higher gradient of the Rus window to the lower gradient of the study area, thus increasing the piezometric head at the study area.

The impact of withdrawals on areas outside the study area was measured in terms of changes in the average piezometric head at the Rus window area. The Rus window area is located to the west of the study area where there is a direct connection between the multiple aquifers in the system. The average piezometric head is greater at the Rus window than in the study area. The decline in the head at the Rus window due to withdrawals from the study area is a measure of regional aquifer depletion. A regression equation was estimated to measure the change in the piezometric head at the Rus window to different annual rates of pumping in the study area. The estimated regression equation was developed as follows:

$$Ph_{ir\,t} = 3.68 + \underset{(125.02)}{0.98}\, Ph_{ir\,t-1} - \underset{(2.82)}{0.00002}\, Q_{iht}$$

where,

$Ph_{ir\,t}$ = average piezometric head in the Rus window in time t, measured in meters.

$Ph_{ir\ t-1}$ = average piezometric head in the Rus window in time t-1, measured in meters.

Q_{iht} = pumping rate in the study area, measured in MCM.

The estimated regression equation had an R^2 of 98 percent and the high T-test values (in parentheses). The average piezometric head at the Rus window area was negatively related to the withdrawals from the study area. Both estimated regression equations were then used as input in the dynamic programming model. These equations allowed the DP model to predict the impact of withdrawals of water in the study area on the average piezometric head in the study area.

Dynamic Programming Model

The results of the parametric linear programming models, investment costs, and groundwater model were used in a dynamic programming model to determine the optimal temporal use of groundwater resources and other limiting resources in the study area which generates the highest discounted net social benefits (NSB). In the DP step, the planning horizon was divided into N decision stages or years. Each stage represented one year in the time horizon from 1990 to 2050. Each stage was associated with a number of state variables. *The state variables* associated with each stage were: the number of existing wells; the irrigated land area; and the piezometric head (remaining water supply). *The decision variables* at each stage were: increasing or decreasing the number of drilled irrigation wells, increasing or decreasing the area developed for irrigation, and determining the maximum amount of groundwater used.

In the DP model, the full depth from the initial water table to the bottom of the UER aquifer (0 to 700 meters) was divided into 101 levels. The LP solutions provided estimates of the NSB for five of the 101 levels of the required piezometric water table. The estimates of annual NSB for each of the 19 levels between levels for which LP solutions were solved were estimated by linear interpolation. Interpolation was used along the time axis as well. Solutions at the various depths were obtained every 15 years. Thus, the NSB for a particular depth in a given year were usually the result of linear interpolations between the NSB from two LP solutions along the depth axis and two LP solutions along the time axis. The interpolation was done to reduce the number of LP solutions which were necessary to obtain to fill out the return table for the DP model.

The planning horizon of interest was 1990 through 2050. To reduce the impact of the ending period, the data for the year 2050 were replicated an additional three times, so, the actual solutions were over a 105 year period. However, the results from the last 45 years were discarded and only the projections from 1990 through 2050 were presented.

Surface Irrigation System

Table LV delineates the optimal plan decisions in the study area if surface irrigation systems were used. The optimal decisions were made at two discount rates: 0 and 5 percent. The optimal decisions were made given the initial states in the study area: 8000 hectares of irrigated land, 300 wells, and the piezometric head at ground surface or 150 meters above sea level.

If the discount rate was zero, the optimal decision would be to develop the maximum possible irrigated area and drill the maximum number of irrigation wells. The optimal plan with a surface irrigation system showed that it would be profitable to increase the irrigated land from 8000 to 20000 hectares, increase the number of irrigation wells from 300 to 750 wells, and use up to 350 MCM of water annually all through the planning horizon. Increasing the annual discharge of wells in the study area from its initial level of 208.80 MCM to 350 MCM would cause the initial piezometric head to decline by 52 meters by the year 2050. The optimal plan would generate discounted net social benefits of 2190 million Riyals. That is, the optimal plan will pay all its expenses and generate an additional 2190 million Riyals over the planning horizon.

At the 0.05 discount rate, the optimal plan calls for immediately increasing the irrigated land from 8000 to 16000 hectares which would be maintained through the year 2010 and

TABLE LV

OPTIMAL LONG-TERM DECISIONS WITH THE SURFACE IRRIGATION SYSTEMS

Year	0.0 Discount Rate (%)					0.05 Discount Rate (%)				
	DRWL (well)	DVLD (ha)	MAWY (MCM/yr)	WRDN (m)	CNPV (MSR)	DRWL (well)	DVLD (ha)	MAWY (MCM/yr)	WRDN (m)	CNPV (MSR)
1995	750	20000	350	3	-245	450	16000	330	3	13
2000	750	20000	350	8	-3	450	16000	330	7	161
2005	750	20000	350	12	237	450	16000	330	11	275
2010	750	20000	350	17	413	600	20000	390	16	282
2015	750	20000	350	21	656	600	20000	390	21	369
2020	750	20000	350	25	898	600	20000	390	26	437
2025	750	20000	350	30	1070	600	20000	390	31	474
2030	750	20000	350	34	1311	600	20000	390	36	516
2035	750	20000	350	38	1550	600	20000	390	41	548
2040	750	20000	350	43	1718	600	20000	390	45	565
2045	750	20000	350	47	1955	600	20000	390	50	585
2050	750	20000	350	52	2190	600	20000	390	55	600

Abbreviations used:
DRWL = number of drilled wells
DVLD = developed irrigated land.
MAWY = annual water use.
WRDN = decline of the actual piezometric head.
CNPV = cumulative net preset value.
MSR = million Saudi Riyals.

then to further increase the area to 20000 hectares which would be maintained through the year 2050. Simultaneously, number of irrigation wells would be increased from 300 to 450 wells from which 330 MCM of water would be used annually up to year 2005. In the year 2010 an additional 150 wells would be added, bringing the total to 600 wells. Annual water use would be 390 MCM per year from 2010 to the end of the planning horizon. The initial piezometric head will decline accordingly by 55 meters by the year 2050. The discounted NSB from the optimal plan would be 600 million Riyals. In other words, the optimal plan would allow all investments to be repaid at 5 percent annually and would generate an additional NSB of 600 million Riyals.

Sprinkler Irrigation System

Table LVI shows the optimal long-term decisions in the study area if sprinkler irrigation systems were adopted and returns were discounted at 0 and 5 percent. If a zero (0.05) discount rate was used, the optimal plan would be to extend the irrigated area from 8000 (8000)to 20000 (20000) hectares and drill an additional 300 (150) irrigation wells. This number would be used throughout the planning horizon. The annual water use fluctuates from time to time starting at 280 (320) MCM in the first planning years to 330 (290) MCM at the end of the planning horizon. This increase was because of the expected increase in population by the year 2050. The initial

TABLE LVI

OPTIMAL LONG-TERM DECISIONS WITH THE SPRINKLER IRRIGATION SYSTEMS

	0.0 Discount Rate (%)					0.05 Discount Rate (%)				
Year	DRWL (well)	DVLD (ha)	MAWY (MCM/yr)	WRDN (m)	CNPV (MSR)	DRWL (well)	DVLD (ha)	MAWY (MCM/yr)	WRDN (m)	CNPV (MSR)
1995	600	20000	280	3	-167	450	20000	320	3	-42
2000	600	20000	280	6	20	450	20000	310	7	86
2005	600	20000	280	10	206	450	20000	310	11	186
2010	600	20000	280	13	302	450	20000	300	15	219
2015	600	20000	280	17	493	450	20000	300	19	281
2020	600	20000	270	20	684	450	20000	300	22	329
2025	600	20000	280	24	784	450	20000	290	26	346
2030	600	20000	280	27	979	450	20000	290	30	376
2035	600	20000	330	31	1176	450	20000	290	33	399
2040	600	20000	330	35	1284	450	20000	290	37	407
2045	600	20000	330	39	1486	450	20000	290	41	422
2050	600	20000	330	43	1686	450	20000	290	44	433

Abbreviations used:
DRWL = number of drilled wells
DVLD = developed irrigated land.
MAWY = annual water use.
WRDN = decline of the actual piezometric head.
CNPV = cumulative net preset value.
MSR = million Saudi Riyals.

piezometric head would decline by 43 (44) meters in year 2050. The optimal plan would generate an additional 1686 (433) million Riyals in discounted benefits over costs.

Trickle Irrigation System

Table LVII presents the optimal long-term decisions in the study area if trickle irrigation systems were adopted and returns were discounted at zero and 5 percent. If a zero (0.05) discount rate was used, the optimal decisions would be to develop 20000 (16000) hectares and drill 450 (300) irrigation wells. Annual water use would be 235 (205) MCM. The initial piezometric head in the study area would drop by 35 (31) meters by the end of the planning horizon. Decisions made under the zero (0.05) discount rate would compensate the investors at the given discount rate and produce an additional 1364 (384) million Riyals of discounted net social benefits.

Complete results of the long-term optimal plan with surface, sprinkler, and trickle systems at two discount rates (0.0, 0.05) are shown in *Tables LXII-LXVII in the Appendix.*

Comparison of Optimal Decisions by Irrigation System

The results presented in *Tables LV-LVII* showed that using surface irrigation system would generate the highest discounted net social benefits with each discount rate, followed by sprinkler system, and then trickle system. On the other hand, trickle system would show more efficient use of irrigation water per a unit of land in comparison to the other

TABLE LVII

OPTIMAL LONG-TERM DECISIONS WITH THE TRICKLE IRRIGATION SYSTEMS

	0.0 Discount Rate (%)					0.05 Discount Rate (%)				
Year	DRWL (well)	DVLD (ha)	MAWY (MCM/yr)	WRDN (m)	CNPV (MSR)	DRWL (well)	DVLD (ha)	MAWY (MCM/yr)	WRDN (m)	CNPV (MSR)
1995	450	20000	250	3	-77	300	16000	200	2	60
2000	450	20000	250	6	94	300	16000	200	5	159
2005	450	20000	250	9	263	300	16000	200	7	236
2010	450	20000	210	12	272	300	16000	210	10	235
2015	450	20000	210	14	444	300	16000	210	12	283
2020	450	20000	210	17	616	300	16000	210	15	321
2025	450	20000	210	19	628	300	16000	210	18	321
2030	450	20000	210	22	805	300	16000	210	20	345
2035	450	20000	260	25	982	300	16000	210	23	363
2040	450	20000	250	28	1000	300	16000	200	26	364
2045	450	20000	250	31	1182	300	16000	200	28	375
2050	450	20000	250	35	1364	300	16000	200	31	384

Abbreviation used:
DRWL = number of drilled wells
DVLD = developed irrigated land.
MAWY = annual water use.
WRDN = decline of the actual piezometric head.
CNPV = cumulative net preset value.
MSR = million Saudi Riyals.

irrigation systems.

Effect of the Discount Rate, Population Growth, and Expenditures on Development Decisions

The choice of discount rate level is a critical decision which reflects the willingness of the society to choose between present and future returns. The higher the discount rate, the lower the discounted future return. The higher discount rate gives more value to systems which provide immediate net benefits. The zero discount rate places equal value on current and future NSB.

Increased population growth implies that marginal NSB from each unit of non-renewable groundwater would be worth more at the end of the planning horizon than at the beginning. Thus, population growth and the higher discount rate have opposite effects on the time in which a non-renewable resource is used.

The capital expenditures for the wells and the distribution systems also interact to affect the timing and use of groundwater. The distribution system must be replaced after each 15 year planning period but the wells can be used in later periods. When the discount rate is zero, there is an incentive to drill the wells early in the planning period. However, the higher discount raises the cost of holding excess well capacity, which provides an incentive to delay the drilling of wells until they can be fully utilized and also to reduce the number of wells which are drilled. The relatively lower capital cost of the distribution systems creates an incentive to spread the water from a given number of wells over as large an area as possible.

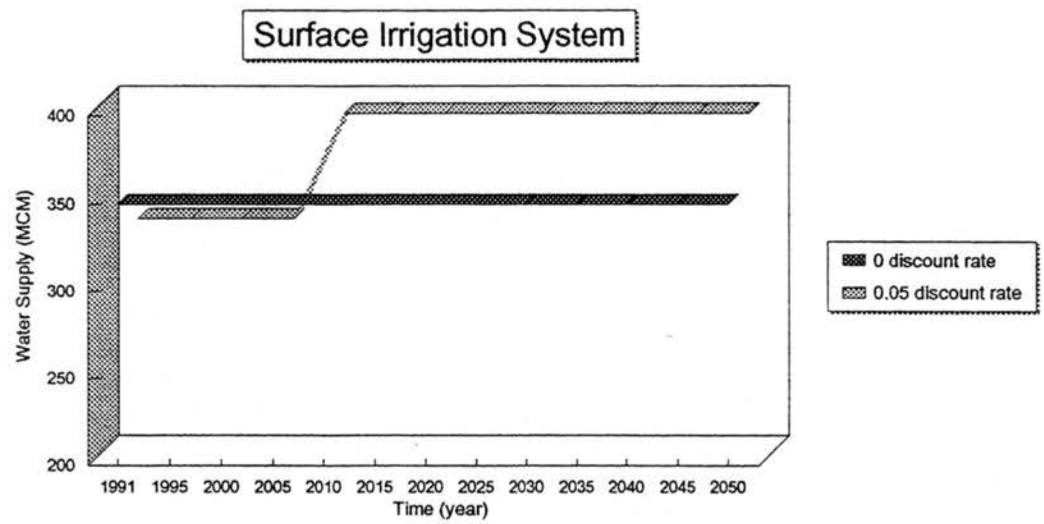
With the surface irrigation system, the optimal allocation of groundwater resources at a zero discount rate is to use 350 MCM annually. At a 0.05 discount rate, it was optimal to supply water at an increasing rate, from 330 MCM annually in the early stages to 390 MCM annually at the later stages.

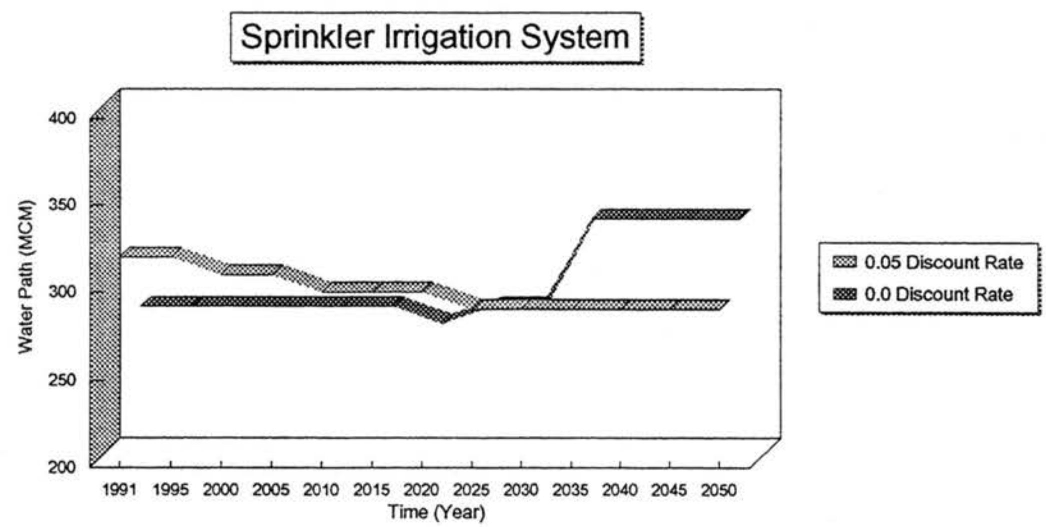
With the sprinkler irrigation system and a zero discount rate, it was optimal to maintain the initial pumping rate until 2030 and then increase the annual water use to 330 MCM annually. At the higher discount rate, the optimal decision was to pump 320 MCM of water in the beginning but to lower the pumping rate over time.

With the trickle irrigation system and a zero discount rate, it was optimal to pump 250 MCM in the early and later stages, but lower the rate of pumping slightly at the mid stages. At a 0.05 discount rate, however, the optimal decision was to maintain a fairly low rate of pumping over the entire planning horizon. *Figure XV* shows the optimal path of groundwater resources over time using different irrigation systems.

Optimal Temporal Allocation of Irrigated Area

Figure XVI illustrates the optimal area of each crop





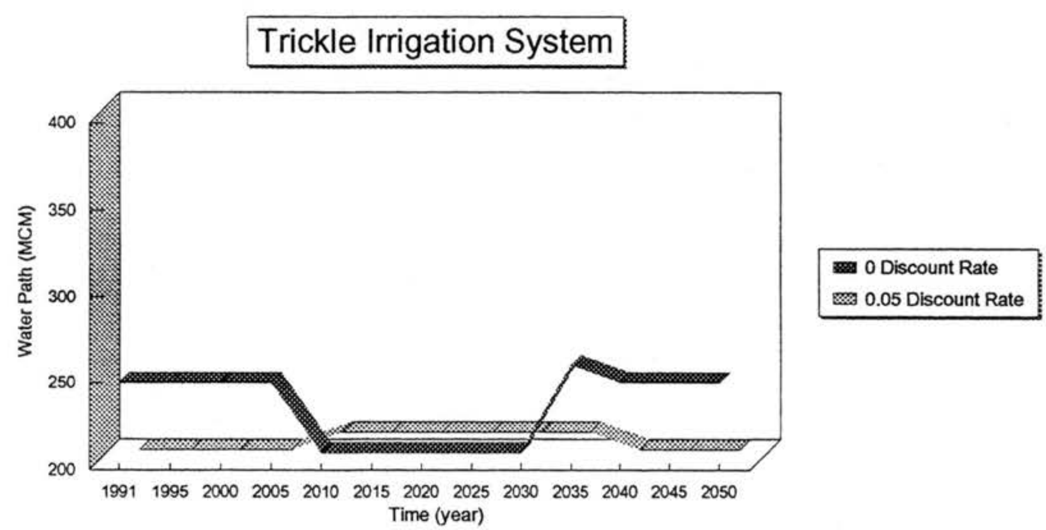
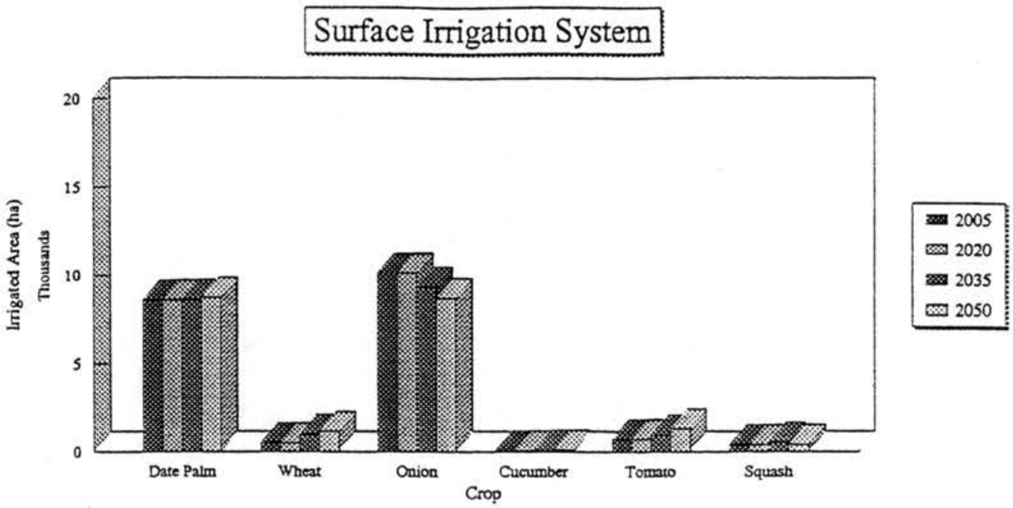
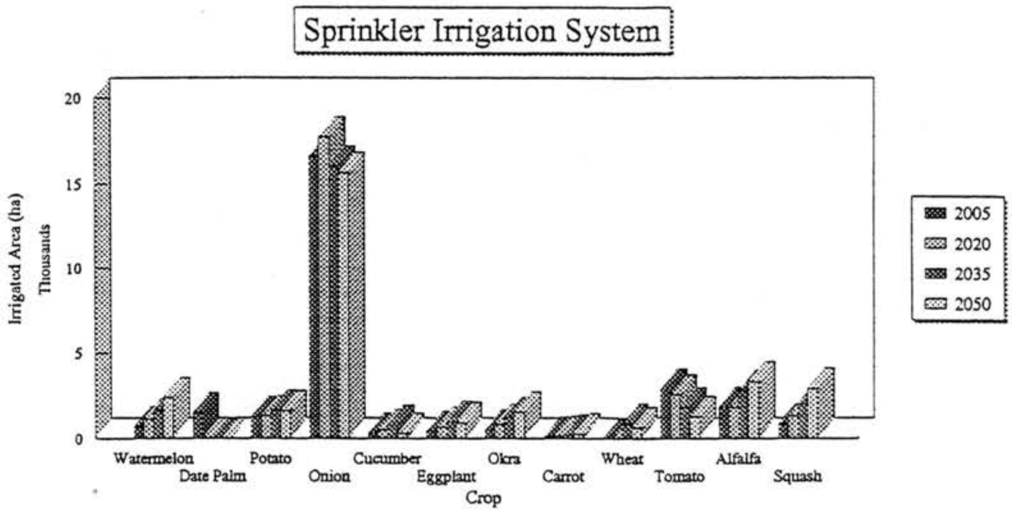


FIGURE XV. OPTIMAL WATER USE WITH DIFFERENT IRRIGATION SYSTEMS





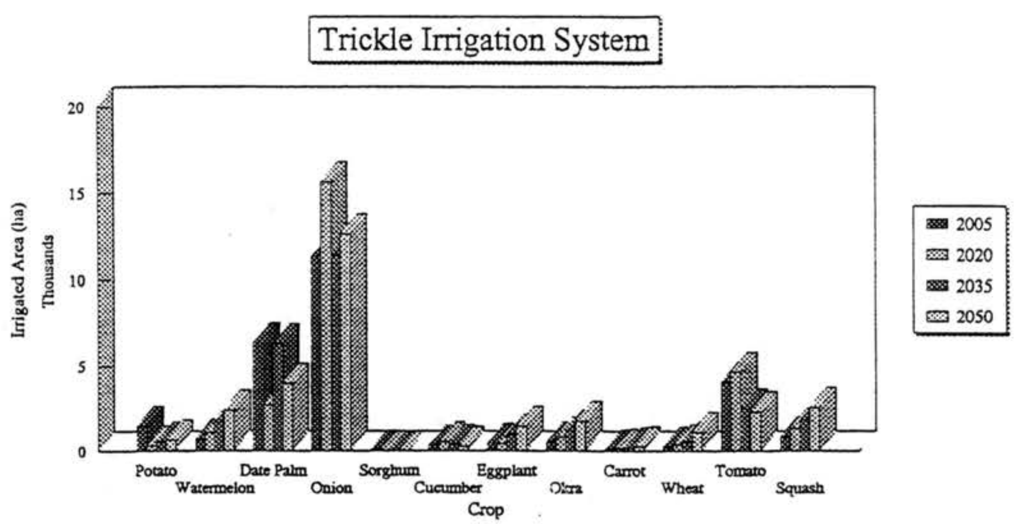


FIGURE XVI. OPTIMAL ALLOCATION OF IRRIGATED AREA USING DIFFERENT IRRIGATION SYSTEMS WITH A ZERO DISCOUNT RATE to be irrigated in the study area from year 2005 to year 2050 using different irrigation systems if the discount rate was zero. *Figure XVII* illustrates the optimal area of each crop to be irrigated in the study area from year 2005 to year 2050 with different irrigation systems if the discount rate was 0.05.

At both discount rates, a larger area would be used for date palm and fewer hectares used for carrots with the surface system than if the sprinkler or trickle systems were used. With the sprinkler system and trickle system, the optimal plan would be to allocate more irrigated land area to dry onion and less to date palm.

The higher capital costs of trickle and sprinkler distribution systems would make growing date palm less attractive than dry onions. *Tables LVIII and LIX* present the data showing the optimal allocation of the irrigated land area in the study area with different irrigation systems at zero and 0.05 percent discount rates.

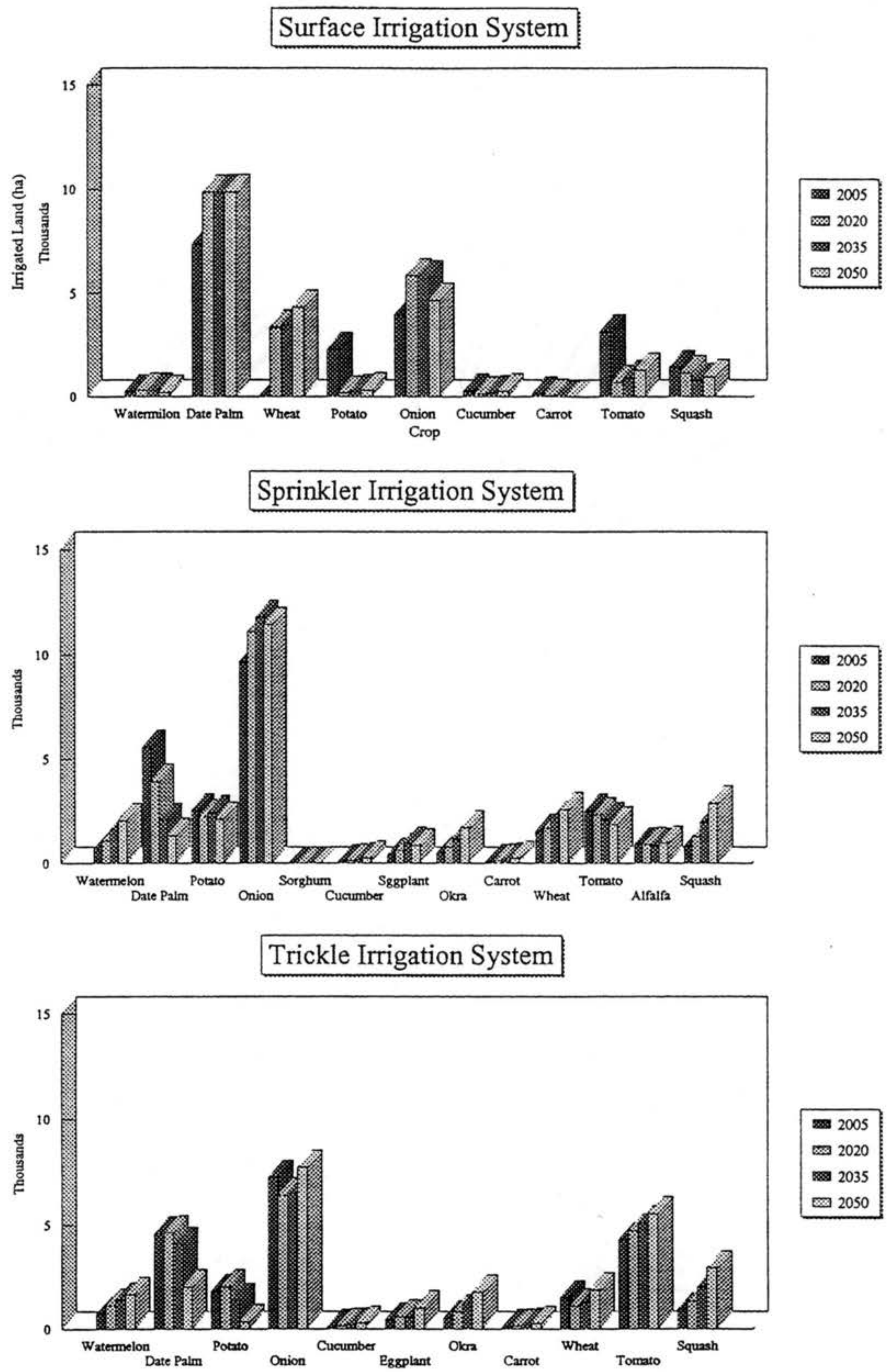


FIGURE XVII. OPTIMAL ALLOCATION OF IRRIGATED AREA USING DIFFERENT IRRIGATION SYSTEMS WITH A 0.05 DISCOUNT RATE

TABLE LVIII

OPTIMAL ALLOCATION OF IRRIGATED AREA AMONG CROPS IN THE STUDY AREA, BY IRRIGATION SYSTEM, WITH A ZERO DISCOUNT RATE.

(HECTARES)

	Surface Irrigation System				Sprinkler Irrigation System				Trickle Irrigation System			
Year / Crop	2005	2020	2035	2050	2005	2020	2035	2050	2005	2020	2035	2050
Watermelon				717	1104	1655	2372	717	1104	1655	2372	
Date Palm	8596	8596	8625	8722	1506	0	0	0	6350	2695	6282	3918
Potato					1275	1310	1640	1603	1468	299	509	641
Dry Onion	10108	10108	9293	8662	16610	17727	16036	15655	11334	15672	11416	12633
Cucumber	52	52	71	96	334	513	767	271	334	513	368	271
Eggplant					428	659	986	908	428	414	986	1412
Okra					527	812	1218	1546	527	812	1218	1745
Carrot					108	146	197	266	108	146	197	266
Wheat	480	480	978	1124	0	0	853	614	240	370	542	1071
Tomato	693	693	937	1267	2894	2560	1806	1267	3983	4587	2452	2275
Alfalfa					1842	1815	2804	3328				
Squash	386	386	521	372	843	1327	2019	2916	843	1327	1798	2525
Sorghum									22	0	0	0
Total	20315	20315	20425	20242	27084	27972	29982	30746	26353	27940	27425	29131

TABLE LIX

OPTIMAL ALLOCATION OF IRRIGATED AREA AMONG CROPS IN THE STUDY AREA, BY IRRIGATION SYSTEM, WITH A 0.05 DISCOUNT RATE.

(HECTARES)

	Surface Irrigation System				Sprinkler Irrigation System				Trickle Irrigation System			
Crop / Year	2005	2020	2035	2050	2005	2020	2035	2050	2005	2020	2035	2050
Watermelon	236	318	319	189	717	1104	1655	2088	717	1104	1382	1642
Date Palm	7361	9852	9867	9867	5561	3943	2093	1371	4574	4616	4065	2016
Potato	2265	181	244	330	2561	2267	2470	2146	1787	2010	1346	330
Dry Onion	3948	5853	5738	4650	9687	11104	11771	11430	7221	6389	6473	7701
Cucumber	271	148	201	271	110	148	201	271	110	148	201	271
Eggplant					428	659	986	884	428	568	552	996
Okra					527	812	1218	1745	527	812	1218	1745
Carrot	146	56			108	146	197	266	108	146	197	266
Wheat		3344	3501	4324	1583	1722	2195	2626	1498	1093	1267	1859
Tomato	3137	693	937	1267	2550	2364	2128	1922	4274	4694	5081	5506
Alfalfa					934	947	898	1004				
Squash	1403	1156	793	975	843	1327	2019	2916	897	1327	2019	2916
Total	18766	21602	21601	21874	25606	26544	27831	28669	22140	22909	23800	25248

CHAPTER V

SUMMARY AND CONCLUSIONS

A linear-dynamic programming model capable of determining the optimal allocation of a multi-aquifer system and crop production in Al-Hassa area was developed and tested. The multi-aquifer system was visualized as a bi-aquifer system including: Neogene-Dammam, and Umm-Er-Radhuma. Most emphasis was given to development of the Umm-Er-Radhuma aquifer. The linear-dynamic programming model consisted of three interrelated steps: i) a parametric linear programming model step (PLP); ii) a groundwater flow model step (GF); and iii) a dynamic programming model step (DP).

The main objective of the study was to develop and test a preliminary model that could be used to determine the most efficient use of the multi-aquifer system for crop production in Al-Hassa area. The model was tested with surface, sprinkler, and trickle irrigation systems. More specifically, this study attempted to: i) determine the optimal crop mixes that would give the highest annual net social benefits; and ii) determine the consequences of the future development on the piezometric heads in Al-Hassa area; and iii) determine the optimal temporal investment and resource utilization decisions that give the highest discounted net social benefits.

The parametric linear programming model provided a series of annual solutions which show the maximum net social benefits associated with different combinations of: i)irrigation wells; ii)irrigated land; and iii)annual water use in the study area from selected aquifer levels. The series of annual solutions were obtained for each irrigation system. This series of PLP solutions was used as inputs to the dynamic programming model.

The groundwater flow model was used to simulate the multi-groundwater-aquifer system in the study area. The simulated model was used to measure the hydraulic response of the piezometric heads to different rates of pumping over a 100 year period. The groundwater flow model provided the link between the amount of aquifer decline and the annual rate of groundwater use.

The dynamic programming model was the last step. The model was used to determine the temporal allocation of the multi-groundwater-aquifer system in the study area that gives the highest discounted net social benefits.

The findings of the PLP model showed the surface irrigation system would generate the highest annual NSB over the other systems. Th surface system would generate 874 million Riyals compared to 869 million Riyals with the sprinkler system, and 867 million Riyals with the trickle system.

On the other hand, the trickle irrigation system was superior to the other irrigation systems in terms of the efficient use of water. The water applied to the irrigated land generated an net social benefits of 5.90 Riyals/m^3 with the trickle system compared to 4.50 Riyals/m^3 with the sprinkler system and 3.73 Riyals/m^3 with surface system.

Preliminary findings of the groundwater flow model showed that the average piezometric head in the study area will decline in response to the withdrawals from the study area. A three fold increase in the initial annual pumping would lower the piezometric head by more than 100 meters.

The findings of the dynamic programming model indicated that the model is capable of providing optimal irrigation decisions in the study area. The optimal temporal path of water use was established for three different irrigation systems in combination with two discount rates. The DP optimal plans using different irrigation systems were measured at zero and 5 percent discount rates. The optimal decisions were found to be promising in terms of increasing efficiency of resource use and net benefits.

The surface irrigation system showed the greatest expected annual net return and discounted net social benefits followed by the sprinkler irrigation system and then the trickle irrigation system. The optimal long-term plan with surface irrigation system would generate 2190 (600) million Riyals if zero (0.05) discount rate were used compared to 1686 (433) million Riyals with sprinkler system, and 1364 (384) million Riyals with trickle system. In another words, investment in irrigated land in the study area would cover all costs and generate additional returns to producers in particular and society in general.

Generally speaking, it appears that irrigation development in the study area is a promising investment when the limited water resources are used efficiently. Surface irrigation system will be superior over the other irrigation systems in terms of net returns.

Limitations of the Study

The findings of the study are limited by the accuracy of the data used in the analysis. The availability of information about the non-renewable groundwater aquifers is of high importance to the study (transmissivity, storativity, piezometric head, and thickness). Unfortunately, this information is not available or/and accessible to researchers. The developed groundwater model for the study can be easily revised as more precise information on the aquifer is determined. Further research is urgently needed on all non-renewable groundwater reserves in Saudi Arabia because of the substantial role of this source to the development process in all national sectors.

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APPENDIX

TABLE LX

ESTIMATED TRANSMISSIVITIES FOR THE NEOGENE-DAMMAM AQUIFER

(SQUARE METERS/DAY)

Width (10 Km)	Cross Section Length (10 Km)																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	0	0	0	0	0	0	822	773	465	549	412	308	51	501	308	68
2	0	0	0	0	0	0	0	822	779	415	498	378	308	29	458	68	68
3	0	0	0	0	0	0	0	0	792	603	464	638	95	667	308	68	308
4	0	0	0	0	0	0	0	0	512	403	272	346	8	386	182	40	240
5	0	0	0	0	0	0	0	0	491	420	266	326	389	384	182	40	240
6	0	0	0	0	0	0	0	0	485	425	449	302	372	383	40	182	240
7	0	0	0	0	0	0	0	0	480	425	400	263	354	379	40	182	507
8	0	0	0	0	0	0	0	0	466	378	261	197	297	367	40	182	507
9	0	0	0	0	0	0	0	0	460	361	251	167	271	359	40	182	507
10	0	0	0	0	0	0	0	0	460	353	238	153	260	214	182	384	507
11	0	0	0	0	0	0	0	0	468	352	219	148	261	221	384	384	496
12	0	0	0	0	0	0	0	0	485	369	308	159	275	254	384	384	507
13	0	0	0	0	0	0	0	0	505	314	281	109	142	320	384	380	507
14	0	0	0	0	0	0	0	0	505	202	213	136	86	283	346	370	507

TABLE LX (Continued)

Width (10 Km)	Cross Section Length (10 Km)															
	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	308	1171	1171	1171	4	501	664	555	470	210	182	182	182	182	182	182
2	308	1171	1171	1171	56	490	649	531	240	182	182	182	182	182	182	182
3	651	1171	1171	1171	651	525	614	276	182	182	444	182	182	182	182	182
4	507	2589	2589	2589	2589	774	542	182	182	182	444	182	182	182	182	182
5	507	2589	2589	2589	365	774	19	182	182	52	21	182	182	182	182	182
6	507	2589	2589	2589	205	774	240	9	182	444	182	182	182	182	182	182
7	507	2589	2589	1227	241	240	240	9	182	444	182	182	182	182	182	182
8	507	2589	2589	1227	66	240	182	9	182	444	182	182	182	182	182	182
9	507	2589	1227	1957	76	240	182	9	182	444	182	182	182	182	182	182
10	507	2589	709	2261	148	240	182	9	182	444	182	182	182	182	182	182
11	464	2112	1558	170	1876	240	182	182	182	444	182	182	182	182	182	182
12	437	468	1878	437	1733	267	247	182	182	444	182	182	182	182	182	182
13	418	1328	2325	692	1506	240	240	182	182	444	182	182	182	182	182	182
14	512	1751	2676	1227	1227	240	240	182	444	182	182	182	182	182	182	182

TABLE LXI

ESTIMATED TRANSMISSIVITIES FOR THE UMM-ER-RADHUMA AQUIFER

(SQUARE METERS/DAY)

Width (10 Km)	Cross Section Length (10 Km)																
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	11016	11508	11004	9997	8529	6770	4815	9111	14705	5178	6578	8321	9467	8767	9863	7986	10600
2	10525	11508	11508	10458	8819	6965	4958	9111	14705	5468	6234	8505	9221	8767	8767	5479	11036
3	10277	11474	11508	11508	9325	7312	5336	6713	8311	6393	4385	9003	9233	11170	13055	8160	13055
4	9472	11422	11508	11508	9657	7623	5550	3516	8897	14705	4629	9338	7768	10160	13055	15345	9838
5	9372	11316	11384	11508	10154	7975	5724	3516	9056	11508	4792	6363	7951	11620	15342	16460	9034
6	9245	9252	11203	11305	11477	8396	5856	3516	7622	11508	16486	3371	8083	11526	15342	15759	8116
7	9111	9079	10954	10999	11438	8277	5787	3516	6409	8311	13665	3651	8225	11471	15342	15447	11507
8	9011	8915	10618	10229	9365	7487	5497	3516	6185	8659	14705	4049	8377	11342	15342	15342	11507
9	9006	10470	10455	9769	8305	6811	5198	3516	6156	8759	14705	4168	8446	10885	15342	15342	11507
10	9134	9029	8785	7892	7276	6254	4966	3516	6163	8758	14705	4176	8454	9184	10510	11507	11507
11	9369	9381	11598	9894	6652	5963	4897	3516	6220	8656	14705	4081	6276	6528	9792	9792	9792
12	9590	9538	10816	9279	6993	6048	5142	4971	6547	8311	13718	3743	6174	6528	9792	9792	9792
13	9590	9590	9590	8774	6951	6732	5129	5500	6683	8311	13408	3571	8284	9792	9792	9792	9792
14	6393	8525	9590	8636	6905	6726	5908	5869	6848	8311	13327	3556	8473	9792	9792	9792	9792

TABLE LXI (Continued)

Width (10 Km)	Cross Section Length (10 Km)															
	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	8767	6575	6575	6575	3110	1574	64	64	64	64	75	128	128	128	128	128
2	5479	6575	6575	6575	6575	1611	48	64	64	64	128	128	128	128	128	128
3	9792	9792	9792	7326	7326	1670	64	64	128	128	128	128	128	128	128	128
4	9792	9792	9792	7151	7151	2442	64	128	128	128	128	128	128	128	128	128
5	11507	16438	16438	16438	6199	6199	1	128	128	128	128	128	128	128	128	128
6	11507	16438	16438	16438	6199	6199	6199	1	128	128	128	128	128	128	128	128
7	11507	16438	16438	5479	6199	6199	6199	1	128	128	128	128	128	128	128	128
8	11507	16438	16438	5479	6199	6199	6199	1	128	128	128	128	128	128	128	128
9	11507	16438	5479	8117	6199	6199	6199	1	128	128	128	128	128	128	128	128
10	11507	16438	5479	6587	13596	6199	6199	1	128	128	128	128	128	128	128	128
11	9792	7326	3755	4045	5784	10861	128	116	128	128	128	128	128	128	128	128
12	9792	2442	3186	6453	7590	11088	128	112	128	128	128	128	128	128	128	128
13	9792	1495	2536	5910	7943	11250	128	109	119	124	126	127	127	127	128	128
14	9792	3445	6877	4884	8048	11316	128	107	116	121	124	126	127	127	127	128

TABLE LXII

OPTIMAL TEMPORAL INVESTMENT AND RESOURCE UTILIZATION IN THE STUDY AREA WITH THE SURFACE IRRIGATION SYSTEM AND A ZERO DISCOUNT RATE

Year	Irrigation Wells (well)	Irrigated Area (ha)	Head Decline (meter)	Maximum Water Use (MCM)	Annual Return (0000 SR)	Drilling Cost (0000 SR)	Restaging Cost (0000 SR)	System Cost (0000 SR)	Net Annual Return (0000 SR)	Cumulative NSB (0000 SR)
1991	750	20000	0	350	4883	44665	0	4170	-43952	-43952
1992	750	20000	1	350	4876	0	0	0	4876	-39076
1993	750	20000	2	350	4870	0	0	0	4870	-34206
1994	750	20000	3	350	4863	0	0	0	4863	-29343
1995	750	20000	3	350	4857	0	0	0	4857	-24486
1996	750	20000	4	350	4850	0	0	0	4850	-19636
1997	750	20000	5	350	4844	0	0	0	4844	-14792
1998	750	20000	6	350	4837	0	0	0	4837	-9955
1999	750	20000	7	350	4831	0	0	0	4831	-5124
2000	750	20000	8	350	4824	0	0	0	4824	-300
2001	750	20000	9	350	4818	0	0	0	4818	4518
2002	750	20000	10	350	4811	0	0	0	4811	9329
2003	750	20000	10	350	4805	0	0	0	4805	14134
2004	750	20000	11	350	4798	0	0	0	4798	18932
2005	750	20000	12	350	4792	0	0	0	4792	23724
2006	750	20000	13	350	4913	0	0	6950	-2037	21687
2007	750	20000	14	350	4907	0	0	0	4907	26594
2008	750	20000	15	350	4900	0	0	0	4900	31494
2009	750	20000	16	350	4894	0	0	0	4894	36388
2010	750	20000	17	350	4887	0	0	0	4887	41275
2011	750	20000	17	350	4880	0	0	0	4880	46155
2012	750	20000	18	350	4874	0	0	0	4874	51029
2013	750	20000	19	350	4867	0	0	0	4867	55896
2014	750	20000	20	350	4861	0	0	0	4861	60757
2015	750	20000	21	350	4854	0	0	0	4854	65611
2016	750	20000	22	350	4848	0	0	0	4848	70459
2017	750	20000	23	350	4841	0	0	0	4841	75300
2018	750	20000	24	350	4835	0	0	0	4835	80135
2019	750	20000	24	350	4828	0	0	0	4828	84963
2020	750	20000	25	350	4822	0	0	0	4822	89785
2021	750	20000	26	350	4854	0	0	6950	-2096	87689
2022	750	20000	27	350	4848	0	0	0	4848	92537
2023	750	20000	28	350	4841	0	0	0	4841	97378
2024	750	20000	29	350	4835	0	0	0	4835	102213
2025	750	20000	30	350	4828	0	0	0	4828	107041
2026	750	20000	31	350	4822	0	0	0	4822	111863
2027	750	20000	31	350	4815	0	0	0	4815	116678
2028	750	20000	32	350	4809	0	0	0	4809	121487
2029	750	20000	33	350	4802	0	0	0	4802	126289
2030	750	20000	34	350	4795	0	0	0	4795	131084
2031	750	20000	35	350	4789	0	0	0	4789	135873
2032	750	20000	36	350	4782	0	0	0	4782	140655
2033	750	20000	37	350	4776	0	0	0	4776	145431
2034	750	20000	38	350	4769	0	0	0	4769	150200
2035	750	20000	38	350	4763	0	0	0	4763	154963
2036	750	20000	39	350	4778	0	0	6950	-2172	152791
2037	750	20000	40	350	4771	0	0	0	4771	157562
2038	750	20000	41	350	4765	0	0	0	4765	162327
2039	750	20000	42	350	4758	0	0	0	4758	167085
2040	750	20000	43	350	4752	0	0	0	4752	171837
2041	750	20000	44	350	4745	0	0	0	4745	176582
2042	750	20000	45	350	4739	0	0	0	4739	181321
2043	750	20000	45	350	4732	0	0	0	4732	186053
2044	750	20000	46	350	4726	0	0	0	4726	190779
2045	750	20000	47	350	4719	0	0	0	4719	195498
2046	750	20000	48	350	4712	0	0	0	4712	200210
2047	750	20000	49	350	4706	0	0	0	4706	204916
2048	750	20000	50	350	4699	0	0	0	4699	209615
2049	750	20000	51	350	4693	0	0	0	4693	214308
2050	750	20000	52	350	4686	0	0	0	4686	218994

The initial state variables: 300 wells, and 8000 hectares of land area.

TABLE LXIII

OPTIMAL TEMPORAL INVESTMENT AND RESOURCE UTILIZATION IN THE STUDY AREA WITH THE SURFACE IRRIGATION SYSTEM AND A 0.05 DISCOUNT RATE

Year	Irrigation Wells (well)	Irrigated Area (ha)	Head Decline (meter)	Maximum Water Use (MCM)	Annual Return (0000 SR)	Drilling Cost (0000 SR)	Restaging Cost (0000 SR)	System Cost (0000 SR)	Net Annual Return (0000 SR)	Cumulative NSB (0000 SR)
1991	450	16000	0	330	4187	14921	0	2780	-13514	-13514
1992	450	16000	1	330	4181	0	0	0	4181	-9532
1993	450	16000	2	330	4176	0	0	0	4176	-5744
1994	450	16000	2	330	4170	0	0	0	4170	-2142
1995	450	16000	3	330	4164	0	0	0	4164	1284
1996	450	16000	4	330	4158	0	0	0	4158	4541
1997	450	16000	5	330	4152	0	0	0	4152	7640
1998	450	16000	6	330	4146	0	0	0	4146	10586
1999	450	16000	7	330	4141	0	0	0	4141	13389
2000	450	16000	7	330	4135	0	0	0	4135	16055
2001	450	16000	8	330	4129	0	0	0	4129	18589
2002	450	16000	9	330	4123	0	0	0	4123	21000
2003	450	16000	10	330	4117	0	0	0	4117	23292
2004	450	16000	11	330	4112	0	0	0	4112	25473
2005	450	16000	11	330	4106	0	0	0	4106	27547
2006	600	20000	12	390	5135	14872	0	6950	-16687	19520
2007	600	20000	13	390	5127	0	0	0	5127	21869
2008	600	20000	14	390	5118	0	0	0	5118	24102
2009	600	20000	15	390	5110	0	0	0	5110	26225
2010	600	20000	16	390	5102	0	0	0	5102	28244
2011	600	20000	17	390	5094	0	0	0	5094	30164
2012	600	20000	18	390	5086	0	0	0	5086	31990
2013	600	20000	19	390	5077	0	0	0	5077	33725
2014	600	20000	20	390	5069	0	0	0	5069	35376
2015	600	20000	21	390	5061	0	0	0	5061	36945
2016	600	20000	22	390	5053	0	0	0	5053	38437
2017	600	20000	23	390	5045	0	0	0	5045	39856
2018	600	20000	24	390	5036	0	0	0	5036	41205
2019	600	20000	25	390	5028	0	0	0	5028	42487
2020	600	20000	26	390	5020	0	0	0	5020	43707
2021	600	20000	27	390	5084	0	0	6950	-1866	43275
2022	600	20000	28	390	5076	0	0	0	5076	44394
2023	600	20000	29	390	5068	0	0	0	5068	45457
2024	600	20000	30	390	5060	0	0	0	5060	46469
2025	600	20000	31	390	5052	0	0	0	5052	47430
2026	600	20000	32	390	5044	0	0	0	5044	48345
2027	600	20000	33	390	5035	0	0	0	5035	49214
2028	600	20000	34	390	5027	0	0	0	5027	50041
2029	600	20000	35	390	5019	0	0	0	5019	50827
2030	600	20000	36	390	5011	0	0	0	5011	51574
2031	600	20000	37	390	5003	0	0	0	5003	52285
2032	600	20000	38	390	4995	0	0	0	4995	52961
2033	600	20000	39	390	4987	0	0	0	4987	53603
2034	600	20000	40	390	4979	0	0	0	4979	54214
2035	600	20000	41	390	4971	0	0	0	4971	54795
2036	600	20000	41	390	4995	0	0	6950	-1955	54577
2037	600	20000	42	390	4987	0	0	0	4987	55106
2038	600	20000	43	390	4979	0	0	0	4979	55609
2039	600	20000	44	390	4971	0	0	0	4971	56087
2040	600	20000	45	390	4962	0	0	0	4962	56541
2041	600	20000	46	390	4954	0	0	0	4954	56973
2042	600	20000	47	390	4946	0	0	0	4946	57384
2043	600	20000	48	390	4938	0	0	0	4938	57774
2044	600	20000	49	390	4930	0	0	0	4930	58146
2045	600	20000	50	390	4922	0	0	0	4922	58499
2046	600	20000	51	390	4914	0	0	0	4914	58834
2047	600	20000	52	390	4906	0	0	0	4906	59154
2048	600	20000	53	390	4898	0	0	0	4898	59457
2049	600	20000	54	390	4890	0	0	0	4890	59746
2050	600	20000	55	390	4882	0	0	0	4882	60020

The initial state variables: 300 wells, and 8000 hectares of land area.

TABLE LXIV

OPTIMAL TEMPORAL INVESTMENT AND RESOURCE UTILIZATION IN THE STUDY AREA WITH THE SPRINKLER IRRIGATION SYSTEM AND A ZERO DISCOUNT RATE

Year	Irrigation Wells (well)	Irrigated Area (ha)	Head Decline (meter)	Maximum Water Use (MCM)	Annual Return (0000 SR)	Drilling Cost (0000 SR)	Restaging Cost (0000 SR)	System Cost (0000 SR)	Net Annual Return (0000 SR)	Cumulative NSB (0000 SR)
1991	600	20000	0	280	3764	29744	0	5727	-31707	-31707
1992	600	20000	1	280	3760	0	0	0	3760	-27947
1993	600	20000	1	280	3756	0	0	0	3756	-24191
1994	600	20000	2	280	3752	0	0	0	3752	-20439
1995	600	20000	3	280	3747	0	0	0	3747	-16692
1996	600	20000	3	280	3743	0	0	0	3743	-12949
1997	600	20000	4	280	3739	0	0	0	3739	-9210
1998	600	20000	5	280	3735	0	0	0	3735	-5475
1999	600	20000	6	280	3731	0	0	0	3731	-1744
2000	600	20000	6	280	3727	0	0	0	3727	1983
2001	600	20000	7	280	3723	0	0	0	3723	5706
2002	600	20000	8	280	3718	0	0	0	3718	9424
2003	600	20000	8	280	3714	0	0	0	3714	13138
2004	600	20000	9	280	3710	0	0	0	3710	16848
2005	600	20000	10	280	3706	0	0	0	3706	20554
2006	600	20000	10	280	3850	0	0	9544	-5694	14860
2007	600	20000	11	280	3846	0	0	0	3846	18706
2008	600	20000	12	280	3843	0	0	0	3843	22549
2009	600	20000	13	280	3839	0	0	0	3839	26388
2010	600	20000	13	280	3835	0	0	0	3835	30223
2011	600	20000	14	280	3831	0	0	0	3831	34054
2012	600	20000	15	280	3828	0	0	0	3828	37882
2013	600	20000	15	280	3824	0	0	0	3824	41706
2014	600	20000	16	280	3820	0	0	0	3820	45526
2015	600	20000	17	280	3816	0	0	0	3816	49342
2016	600	20000	17	280	3813	0	0	0	3813	53155
2017	600	20000	18	270	3809	0	0	0	3809	56964
2018	600	20000	19	270	3805	0	0	0	3805	60769
2019	600	20000	19	270	3802	0	0	0	3802	64571
2020	600	20000	20	270	3798	0	0	0	3798	68369
2021	600	20000	21	280	3929	0	0	9544	-5615	62754
2022	600	20000	22	280	3925	0	0	0	3925	66679
2023	600	20000	22	280	3921	0	0	0	3921	70600
2024	600	20000	23	280	3917	0	0	0	3917	74517
2025	600	20000	24	280	3913	0	0	0	3913	78430
2026	600	20000	24	280	3909	0	0	0	3909	82339
2027	600	20000	25	280	3905	0	0	0	3905	86244
2028	600	20000	26	280	3901	0	0	0	3901	90145
2029	600	20000	26	280	3897	0	0	0	3897	94042
2030	600	20000	27	280	3893	0	0	0	3893	97935
2031	600	20000	28	330	3935	0	0	0	3935	101870
2032	600	20000	29	330	3930	0	0	0	3930	105800
2033	600	20000	29	330	3925	0	0	0	3925	109725
2034	600	20000	30	330	3920	0	0	0	3920	113645
2035	600	20000	31	330	3915	0	0	0	3915	117560
2036	600	20000	32	330	4079	0	0	9544	-5465	112095
2037	600	20000	33	330	4073	0	0	0	4073	116168
2038	600	20000	34	330	4067	0	0	0	4067	120235
2039	600	20000	34	330	4062	0	0	0	4062	124297
2040	600	20000	35	330	4056	0	0	0	4056	128353
2041	600	20000	36	330	4051	0	0	0	4051	132404
2042	600	20000	37	330	4045	0	0	0	4045	136449
2043	600	20000	38	330	4039	0	0	0	4039	140488
2044	600	20000	39	330	4034	0	0	0	4034	144522
2045	600	20000	39	330	4028	0	0	0	4028	148550
2046	600	20000	40	330	4023	0	0	0	4023	152573
2047	600	20000	41	330	4017	0	0	0	4017	156590
2048	600	20000	42	330	4012	0	0	0	4012	160602
2049	600	20000	43	330	4006	0	0	0	4006	164608
2050	600	20000	43	330	4001	0	0	0	4001	168609

The initial state variables: 300 wells, and 8000 hectares of land area.

TABLE LXV

OPTIMAL TEMPORAL INVESTMENT AND RESOURCE UTILIZATION IN THE STUDY AREA WITH THE SPRINKLER IRRIGATION SYSTEM AND A 0.05 DISCOUNT RATE

Year	Irrigation Wells (well)	Irrigated Area (ha)	Head Decline (meter)	Maximum Water Use (MCM)	Annual Return (0000 SR)	Drilling Cost (0000 SR)	Restaging Cost (0000 SR)	System Cost (0000 SR)	Net Annual Return (0000 SR)	Cumulative NSB (0000 SR)
1991	450	20000	0	320	3627	14921	0	5727	-17021	-17021
1992	450	20000	1	320	3622	0	0	0	3622	-13572
1993	450	20000	2	320	3617	0	0	0	3617	-10292
1994	450	20000	2	320	3612	0	0	0	3612	-7172
1995	450	20000	3	320	3607	0	0	0	3607	-4204
1996	450	20000	4	320	3602	0	0	0	3602	-1382
1997	450	20000	5	320	3597	0	0	0	3597	1302
1998	450	20000	6	310	3592	0	0	0	3592	3855
1999	450	20000	6	310	3587	0	0	0	3587	6283
2000	450	20000	7	310	3582	0	0	0	3582	8592
2001	450	20000	8	310	3577	0	0	0	3577	10788
2002	450	20000	9	310	3573	0	0	0	3573	12877
2003	450	20000	9	310	3568	0	0	0	3568	14864
2004	450	20000	10	310	3563	0	0	0	3563	16753
2005	450	20000	11	310	3558	0	0	0	3558	18550
2006	450	20000	12	310	3646	0	0	9544	-5899	15713
2007	450	20000	13	310	3641	0	0	0	3641	17381
2008	450	20000	13	310	3636	0	0	0	3636	18967
2009	450	20000	14	300	3631	0	0	0	3631	20476
2010	450	20000	15	300	3627	0	0	0	3627	21911
2011	450	20000	16	300	3622	0	0	0	3622	23276
2012	450	20000	16	300	3617	0	0	0	3617	24575
2013	450	20000	17	300	3613	0	0	0	3613	25810
2014	450	20000	18	300	3608	0	0	0	3608	26985
2015	450	20000	19	300	3603	0	0	0	3603	28102
2016	450	20000	19	300	3599	0	0	0	3599	29165
2017	450	20000	20	300	3594	0	0	0	3594	30175
2018	450	20000	21	300	3589	0	0	0	3589	31137
2019	450	20000	22	300	3585	0	0	0	3585	32051
2020	450	20000	22	300	3580	0	0	0	3580	32921
2021	450	20000	23	290	3675	0	0	9544	-5869	31563
2022	450	20000	24	290	3671	0	0	0	3671	32372
2023	450	20000	25	290	3666	0	0	0	3666	33141
2024	450	20000	25	290	3662	0	0	0	3662	33873
2025	450	20000	26	290	3658	0	0	0	3658	34570
2026	450	20000	27	290	3653	0	0	0	3653	35232
2027	450	20000	28	290	3649	0	0	0	3649	35862
2028	450	20000	28	290	3645	0	0	0	3645	36461
2029	450	20000	29	290	3640	0	0	0	3640	37031
2030	450	20000	30	290	3636	0	0	0	3636	37574
2031	450	20000	30	290	3632	0	0	0	3632	38089
2032	450	20000	31	290	3627	0	0	0	3627	38580
2033	450	20000	32	290	3623	0	0	0	3623	39047
2034	450	20000	33	290	3619	0	0	0	3619	39491
2035	450	20000	33	290	3614	0	0	0	3614	39913
2036	450	20000	34	290	3717	0	0	9544	-5827	39265
2037	450	20000	35	290	3713	0	0	0	3713	39658
2038	450	20000	36	290	3708	0	0	0	3708	40033
2039	450	20000	36	290	3704	0	0	0	3704	40389
2040	450	20000	37	290	3700	0	0	0	3700	40727
2041	450	20000	38	290	3695	0	0	0	3695	41050
2042	450	20000	38	290	3691	0	0	0	3691	41356
2043	450	20000	39	290	3686	0	0	0	3686	41648
2044	450	20000	40	290	3682	0	0	0	3682	41925
2045	450	20000	41	290	3678	0	0	0	3678	42189
2046	450	20000	41	290	3673	0	0	0	3673	42440
2047	450	20000	42	290	3669	0	0	0	3669	42679
2048	450	20000	43	290	3665	0	0	0	3665	42906
2049	450	20000	44	290	3660	0	0	0	3660	43122
2050	450	20000	44	290	3656	0	0	0	3656	43327

The initial state variables: 300 wells, and 8000 hectares of land area.

TABLE LXVI

OPTIMAL TEMPORAL INVESTMENT AND RESOURCE UTILIZATION IN THE STUDY AREA WITH THE TRICKLE IRRIGATION SYSTEM AND A ZERO DISCOUNT RATE

Year	Irrigation Wells (well)	Irrigated Area (ha)	Head Decline (meter)	Maximum Water Use (MCM)	Annual Return (0000 SR)	Drilling Cost (0000 SR)	Restaging Cost (0000 SR)	System Cost (0000 SR)	Net Annual Return (0000 SR)	Cumulative NSB (0000 SR)
1991	450	20000	0	250	3431	14921	0	9896	-21387	-21387
1992	450	20000	1	250	3428	0	0	0	3428	-17959
1993	450	20000	1	250	3425	0	0	0	3425	-14535
1994	450	20000	2	250	3421	0	0	0	3421	-11113
1995	450	20000	3	250	3418	0	0	0	3418	-7695
1996	450	20000	3	250	3415	0	0	0	3415	-4280
1997	450	20000	4	250	3412	0	0	0	3412	-868
1998	450	20000	4	250	3409	0	0	0	3409	2542
1999	450	20000	5	250	3406	0	0	0	3406	5948
2000	450	20000	6	250	3403	0	0	0	3403	9350
2001	450	20000	6	250	3400	0	0	0	3400	12750
2002	450	20000	7	250	3397	0	0	0	3397	16147
2003	450	20000	8	250	3394	0	0	0	3394	19541
2004	450	20000	8	250	3391	0	0	0	3391	22931
2005	450	20000	9	250	3387	0	0	0	3387	26319
2006	450	20000	9	240	3503	0	0	16494	-12990	13328
2007	450	20000	10	240	3501	0	0	0	3501	16829
2008	450	20000	11	210	3461	0	0	0	3461	20290
2009	450	20000	11	210	3458	0	0	0	3458	23748
2010	450	20000	12	210	3456	0	0	0	3456	27204
2011	450	20000	12	210	3454	0	0	0	3454	30658
2012	450	20000	13	210	3451	0	0	0	3451	34109
2013	450	20000	13	210	3449	0	0	0	3449	37558
2014	450	20000	14	210	3447	0	0	0	3447	41005
2015	450	20000	14	210	3444	0	0	0	3444	44449
2016	450	20000	15	210	3442	0	0	0	3442	47891
2017	450	20000	15	210	3439	0	0	0	3439	51330
2018	450	20000	16	210	3437	0	0	0	3437	54767
2019	450	20000	16	210	3435	0	0	0	3435	58202
2020	450	20000	17	210	3432	0	0	0	3432	61634
2021	450	20000	17	210	3543	0	0	16494	-12951	48683
2022	450	20000	18	210	3540	0	0	0	3540	52223
2023	450	20000	18	210	3538	0	0	0	3538	55761
2024	450	20000	19	210	3536	0	0	0	3536	59297
2025	450	20000	19	210	3533	0	0	0	3533	62830
2026	450	20000	20	210	3531	0	0	0	3531	66361
2027	450	20000	21	210	3528	0	0	0	3528	69889
2028	450	20000	21	210	3526	0	0	0	3526	73415
2029	450	20000	22	210	3524	0	0	0	3524	76939
2030	450	20000	22	210	3521	0	0	0	3521	80460
2031	450	20000	23	260	3554	0	0	0	3554	84014
2032	450	20000	23	260	3550	0	0	0	3550	87564
2033	450	20000	24	260	3547	0	0	0	3547	91112
2034	450	20000	25	260	3544	0	0	0	3544	94656
2035	450	20000	25	260	3541	0	0	0	3541	98197
2036	450	20000	26	250	3666	0	0	16494	-12828	85369
2037	450	20000	26	250	3663	0	0	0	3663	89032
2038	450	20000	27	250	3660	0	0	0	3660	92693
2039	450	20000	28	250	3657	0	0	0	3657	96350
2040	450	20000	28	250	3654	0	0	0	3654	100004
2041	450	20000	29	250	3651	0	0	0	3651	103655
2042	450	20000	30	250	3648	0	0	0	3648	107303
2043	450	20000	30	250	3645	0	0	0	3645	110949
2044	450	20000	31	250	3642	0	0	0	3642	114591
2045	450	20000	31	250	3639	0	0	0	3639	118230
2046	450	20000	32	250	3636	0	0	0	3636	121867
2047	450	20000	33	250	3633	0	0	0	3633	125500
2048	450	20000	33	250	3630	0	0	0	3630	129131
2049	450	20000	34	250	3628	0	0	0	3628	132758
2050	450	20000	35	250	3625	0	0	0	3625	136383

The initial State variables: 300 wells, and 8000 hectares of land area.

TABLE LXVII

OPTIMAL TEMPORAL INVESTMENT AND RESOURCE UTILIZATION IN THE STUDY AREA WITH THE TRICKLE IRRIGATION SYSTEM AND A 0.05 DISCOUNT RATE

Year	Irrigation Wells (well)	Irrigated Area (ha)	Head Decline (meter)	Maximum Water Use (MCM)	Annual Return (0000 SR)	Drilling Cost (0000 SR)	Restaging Cost (0000 SR)	System Cost (0000 SR)	Net Annual Return (0000 SR)	Cumulative NSB (0000 SR)
1991	300	16000	0	200	2783	0	0	6598	-3815	-3815
1992	300	16000	1	200	2780	0	0	0	2780	-1167
1993	300	16000	1	200	2778	0	0	0	2778	1353
1994	300	16000	2	200	2776	0	0	0	2776	3751
1995	300	16000	2	200	2774	0	0	0	2774	6033
1996	300	16000	3	200	2771	0	0	0	2771	8204
1997	300	16000	3	200	2769	0	0	0	2769	10270
1998	300	16000	4	200	2767	0	0	0	2767	12237
1999	300	16000	4	200	2765	0	0	0	2765	14108
2000	300	16000	5	200	2762	0	0	0	2762	15888
2001	300	16000	5	200	2760	0	0	0	2760	17583
2002	300	16000	6	200	2758	0	0	0	2758	19195
2003	300	16000	6	200	2755	0	0	0	2755	20729
2004	300	16000	7	200	2753	0	0	0	2753	22189
2005	300	16000	7	200	2751	0	0	0	2751	23579
2006	300	16000	8	210	2855	0	0	13195	-10340	18605
2007	300	16000	8	210	2852	0	0	0	2852	19912
2008	300	16000	9	210	2850	0	0	0	2850	21155
2009	300	16000	9	210	2847	0	0	0	2847	22338
2010	300	16000	10	210	2845	0	0	0	2845	23464
2011	300	16000	10	210	2842	0	0	0	2842	24535
2012	300	16000	11	210	2840	0	0	0	2840	25555
2013	300	16000	11	210	2838	0	0	0	2838	26525
2014	300	16000	12	210	2835	0	0	0	2835	27448
2015	300	16000	12	210	2833	0	0	0	2833	28326
2016	300	16000	13	210	2830	0	0	0	2830	29162
2017	300	16000	14	210	2828	0	0	0	2828	29957
2018	300	16000	14	210	2825	0	0	0	2825	30714
2019	300	16000	15	210	2823	0	0	0	2823	31434
2020	300	16000	15	210	2820	0	0	0	2820	32119
2021	300	16000	16	210	2897	0	0	13195	-10299	29736
2022	300	16000	16	210	2894	0	0	0	2894	30374
2023	300	16000	17	210	2892	0	0	0	2892	30981
2024	300	16000	17	210	2890	0	0	0	2890	31558
2025	300	16000	18	210	2887	0	0	0	2887	32108
2026	300	16000	18	210	2885	0	0	0	2885	32631
2027	300	16000	19	210	2883	0	0	0	2883	33129
2028	300	16000	19	210	2880	0	0	0	2880	33602
2029	300	16000	20	210	2878	0	0	0	2878	34053
2030	300	16000	20	210	2876	0	0	0	2876	34482
2031	300	16000	21	210	2873	0	0	0	2873	34890
2032	300	16000	21	210	2871	0	0	0	2871	35278
2033	300	16000	22	210	2869	0	0	0	2869	35648
2034	300	16000	22	210	2866	0	0	0	2866	36000
2035	300	16000	23	210	2864	0	0	0	2864	36334
2036	300	16000	24	200	2963	0	0	13195	-10233	35195
2037	300	16000	24	200	2960	0	0	0	2960	35509
2038	300	16000	25	200	2958	0	0	0	2958	35808
2039	300	16000	25	200	2956	0	0	0	2956	36092
2040	300	16000	26	200	2954	0	0	0	2954	36362
2041	300	16000	26	200	2951	0	0	0	2951	36620
2042	300	16000	27	200	2949	0	0	0	2949	36865
2043	300	16000	27	200	2947	0	0	0	2947	37098
2044	300	16000	28	200	2945	0	0	0	2945	37320
2045	300	16000	28	200	2943	0	0	0	2943	37531
2046	300	16000	29	200	2940	0	0	0	2940	37732
2047	300	16000	29	200	2938	0	0	0	2938	37923
2048	300	16000	30	200	2936	0	0	0	2936	38105
2049	300	16000	30	200	2934	0	0	0	2934	38278
2050	300	16000	31	200	2932	0	0	0	2932	38443

The initial state variables: 300 wells, and 8000 hectares of land area.

VITA

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